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OVERVIEW STUDY OF SPACE POWER TECHNOLOGIES FOR THE ADVANCED ENERGETICS PROGRAM

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16. Abstract

Space power technologies are reviewed to determine the state of the art and to identify advanced or novel concepts which promise large increases in performance. The potential for increased performance is judged relative to benchmarks based on technologies which have been flight tested. Space power technology concepts selected for their potentially high performance are prioritized in a list of R & D topical recommendations for the NASA program on Advanced Energetics. This report summarizes work carried out by a committee of scientists and engineers as part of an overview study of advanced energetics by NASA.

The technology categories studied are solar collection, nuclear power sources, energy conversion, energy storage, power transmission, and power processing. The emphasis is on electric power generation in space for satellite on-board electric power, for electric propulsion, or for beamed power to spacecraft. Generic mission categories such as low Earth orbit (LEO) missions and geosynchronous orbit (GEO) missions are used to distinguish general requirements placed on the performance of power conversion technology. Each space power technology is judged on its own merits without reference to specific missions or power systems. The potential for improved performance is estimated from current data, from the committee's own experience, and from their contacts within the scientific community. The viewpoints of both proponents and critics are evaluated. Possible impediments to technological development are also identified wherever possible.

The highest ranked space power concepts are recommended for the advanced energetics program. These recommendations include 31 space power concepts which span the entire collection of technology categories studied and represent the critical technologies needed for higher power, lighter weight, more efficient power conversion in space. A series of studies to further develop data for particular concept evaluation and to explore technology trade-offs in key power systems areas are also recommended.

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Our special thanks go to Mr. Bernard Sater of the NASA-Lewis Research Center for his time, patience and guidance as the contract monitor for this study, to Mr. Sol Gorland and Mr. James Morris for their advice and perspectives on the role of the Advanced Energetics Program at NASA, and to the several reviewers who gave a considerable amount of time and effort to make this a better report.

Section 1
INTRODUCTION

The objective of the Advanced Energetics Program at NASA-Lewis Research Center is to search out and investigate innovative new concepts in energy processing systems which, if successfully developed, could provide substantial improvement over state-of-the-art technologies now envisioned for space missions beyond the 1990s. This overview study was undertaken as a first step in this program. The overview study was performed to (1) define the state of the art of space power technologies, (2) establish "benchmark" standards for comparison of competing technologies on a unified basis as well as to provide a measure against which new and unconventional concepts can be evaluated, (3) address the technological impediments to reveal new research opportunities, and (4) make recommendations on the technological areas with potential for major improvements so that NASA's limited resources for further developments can be directed on a meaningful basis. The purpose of this report is to review the findings and recommendations of the overview study. A summary of those is included at the end of this section.

Future scientific missions, the requirements of man in space, large scale communications systems, propulsion and the new opportunities enabled by the prospect of power beaming are all driving forces in the consideration of advanced space power systems. These forces manifest themselves in the trend toward higher power requirements, higher voltages, higher temperature power conversions and higher waste heat rejection temperatures pushing beyond the capabilities of current technologies. The main issues are the requirements of new missions, the potential ability of advanced technologies to satisfy those needs and the likelihood of realizing that potential. These issues are discussed in a general way below and are treated in detail with respect to specific technologies in later sections of this report.

Previous reviews of advanced space power technologies have generally been limited to specific topics such as energy storage,[1] photovoltaic cells[2], radiation energy conversion in space,[3] or to forecasts of mission requirements[4] and power system requirements.[5] The emphasis here has been to broaden the review to encompass all of the major categories of space power technology and to develop self-consistent priorities for choosing those technologies with the highest payoff, regardless of which category they belong to. The scope of this study is outlined in more detail below, and the methods used to assess and rank advanced technologies are discussed briefly in the following sections. A summary of the major recommendation is presented in Section 1.5.

1.1 Scope

Solar energy collection, nuclear energy sources, energy conversion, energy storage, power transmission, waste heat rejection and power processing technologies are included in the scope of this study. Power systems for producing electrical energy and in some cases heat have been considered. The power output is assumed to be used on-board the spacecraft or for beaming to another spacecraft. Power transmission to ground receivers has been excluded from this study because it lies within the province of the SPS program; however power transmission from the ground up to satellites has been included. Specialized power processing for spacecraft propulsion also lies within the scope of this study, while the precise mechanisms or processes involved in the propulsion unit are not considered. In short the uses of the power output are treated to the extent necessary for characterizing their requirements on the power system.

New and advanced technologies being developed by government, industrial and university groups have been reviewed. The stage of development varies from flight tested systems all the way to concepts not yet even at the laboratory experiment stage. One of the primary objectives of this study has been to sample a wide range of groups involved in research and development on technologies related to space power systems.

Information has been obtained from Department of Energy programs funded in this area as well as from the aerospace industries and other firms involved in relevant research. NASA energetics programs have also been reviewed to determine the state of the art of advanced technology.

1.2 Methodology

A committee of scientists and engineers whose expertise spans the range of advanced space power technology was assembled to carry out this study under the direction of Mathematical Sciences Northwest, Inc. (MSNW). Their review and assessment was carried out over a period of six months through their own individual efforts and as a group in a series of three committee meetings. This report incorporates the committee's assessment and recommendations for R & D in those areas which offer the greatest payoff for improved power system performance.

The review of the state of the art of advanced and new space energetics technologies was based on the personal knowledge of the committee as well as their contacts with colleagues and other workers in the fields which they represent. The committee members were chosen for their reputation and expertise in their specialties and for their ability to synthesize the latest information related to advanced space energetics. The committee members and their responsibilities for this review are listed in Table 1.1. A list of the groups and individuals contacted for data input to this review are in Appendix A. A preliminary draft of the review was circulated for comments and criticism, and these were incorporated wherever appropriate.

A broad range of opinions have been factored into the review and recommendations of this study. A portfolio of views is presented which illuminate key technologies holding high payoff potential for large increases in space power system performance.

In establishing benchmarks for advanced space power systems we have taken the point of view that the most advanced flight-tested systems should be used as the standards. New or advanced space power technology must

Table 1.1

Advanced Energetics Study Committee Members

Name	Affiliation	Primary Area of Responsibility
James R. Powell	Brookhaven National Laboratory	Nuclear Energy Sources
Marcia Neugebauer	Jet Propulsion Laboratory	Space Environment
Wayne M. Phillips	Jet Propulsion Laboratory	Thermoelectric and Thermionic Energy Conversion
Eckart W. Schmidt	Rocket Research Company	Thermal and Chemical Energy Storage
Sidney Gross	Boeing Corporation	Electrochemical Energy Conversion and Electrical Storage
Gordon R. Woodcock	Boeing Corporation	Propulsion, Microwave Power Transmission, and Mission Analysis
Alan R. Millner	TriSolar Corporation	Mechanical Energy Storage and Power Processing
Martin Wolf	University of Pennsylvania	Photovoltaic Energy Conversion
J.J. Ewing	Mathematical Sciences Northwest	Laser Energy Sources and Laser Transmission
Robert T. Taussig	Mathematical Sciences Northwest	Mechanical Energy Conversion

perform significantly better than these benchmarks in order to qualify for attention in the Advanced Energetics Program. Technologies which enable entirely new missions and for which there is no present comparable technology may also qualify. These benchmarks are summarized in each technology discussion of Section 4.

New and advanced energetics technologies not currently under development as well as technologies in current development programs but promising significant advances were investigated in order to determine their potential for surpassing the benchmarks. In many instances the technologies are only in the conceptual stage of development so that scant data were available for assessing their potential. In other cases, experimental data were present so that a reference level of performance could be more firmly established. With this background the reader is forewarned that the estimates of performance improvements are highly qualitative. For that reason we have refrained from making detailed distinctions as to the comparative levels of performance improvements which might be achieved. Instead, we have chosen to focus on those technologies having a clear advantage over present systems or those technologies which attack tough performance limits and which may be instrumental to creating greatly increased performance for a whole class of space power systems.

1.3 Priorities

The criteria for selecting new and advanced technologies for research under the Advanced Energetics Program are

- potential for large, nonincremental improvements in performance,
- enablement of new missions, and
- high payoff for a large number of missions.

Within these criteria we have established individual measures specific to

each of the major subcategories of space energetics technologies to determine their candidacy for this program. For example in the area of photovoltaic cell energy conversion the criteria for performance were based on increased lifetime, high efficiency, lower power-specific mass, reduced price, higher array operating temperatures....for a range of output power conditions from 1 kW to 1 MW. Each candidate technology was subjected to these criteria. Those having the best overall potential for improvements or those with excessively high potential in one or two areas were ranked the highest.

The most difficult aspect of prioritizing our recommendations is related to cutting across the technology categories where comparisons for example of energy storage technology to energy conversion technologies were required. For this purpose we invoked the more global criteria first mentioned in this section. In addition we also considered the finite resources available to the NASA Advanced Energetics program and chose those technologies which would benefit most from seed money rather than those which would require very large initial expenditures to test their potential for improvement.

1.4 Structure of Report

The results of the state-of-the-art review, the technological assessment of new and advanced energetics and recommendations for high payoff technologies are summarized in each subsection in Section 4 by major technology category. This approach had the advantage of allowing us to apply category-specific criteria for ranking technologies before cutting across these boundaries in our final recommendations. The contents of Section 4 are also intended to be the beginning of a catalog of technologies which have been investigated for space energetics along with our opinion of their potential. This format should assist researchers in the field as well as NASA program staff in selecting technologies for further research.

The final two subsections in Section 4 address the broader aspects of new mission enablement and a comparative evaluation of technologies. These two sections introduce some of the critical space power systems issues and trade-offs used to prioritize our final recommendations.

In Section 5 we present our recommendations supported by a discussion of high payoff technologies, R & D priorities, project-area (technology) recommendations, program priorities and program recommendations. A summary of the highest priority recommendations follows.

1.5 Summary of Findings and Recommendations

The state-of-the-art review of advanced space power technologies has led to estimates of the performance limits for each of the major technology areas and to specific needs for improving performance. For example these include a continuing need for improving the performance of the photovoltaic cells, batteries and power processing components now in use as the workhorse power systems for most satellites. Higher power spacecraft will almost uniformly require new or advanced approaches to overcome the stubborn obstacles to scaling up current technology. New techniques are needed for deploying large photovoltaic cell arrays and for making them last much longer in space. Waste heat radiators for thermal power system designs have already reached their natural size limits with heat pipe technology: New heat rejection techniques will be needed for power systems much above several hundred kilowatts in size. Energy storage weight becomes a particularly onerous penalty for LEO and GEO missions as the power requirements rise: New, lightweight energy storage systems are needed.

New mission concepts, such as planetary surface exploration and return and outer planetary travel, also encourage one to consider advanced power technology concepts such as power beaming, compact high-specific-power energy-conversion concepts (like gaseous nuclear reactors), power systems designed for high performance propulsion and novel components to enable these power systems to function at their full potential.

Over one hundred different new and advanced technologies have been assessed in order to determine their potential for improved performance. Many other concepts may have been passed over, and some of these will undoubtably arise in the future as being useful to power system advancement. However our selection attempts to be representative by giving examples of classes of concepts which have been proposed and/or investigated for advanced power systems. By applying the screening process described above in Section 1.2 we arrived at a more select group of prospects to recommend for support under the Advanced Energetics Program.

The technologies judged to have the highest potential payoff in terms of major performance improvement, to have no insurmountable obstacles to achieving these goals and to be applicable to a reasonably large number of mission categories were selected for final recommendation. These were further classified into first priority, second priority and third priority. The six highest priority technologies recommended for the program, without any preference intended by their order, are the following.

- FLYWHEELS FOR ENERGY STORAGE - Flywheels have the near-term potential of doubling the energy storage capabilities of batteries, are capable of retaining their energy for years as opposed to months and for some applications can potentially be combined with satellite attitude control to reduce the weight of two separate components.

- RECUPERATORS FOR HIGH-TEMPERATURE POWER CYCLES - With the use of high-temperature heat sources, Brayton cycles may become very advantageous compared to photovoltaics in terms of power specific weight at high powers. High-temperature recuperators (such as rotating or fluidized bed recuperators) would complement current developments

in high-temperature expanders to make this approach feasible.

- HIGH-TEMPERATURE SOLAR RECEIVERS - These comprise the second key component along with the recuperator in allowing high-temperature solar-thermal power systems to be used in space. The potential for considerably higher-temperature operation exists with advanced receiver concepts which would allow high cycle efficiencies and high- specific-power solar-thermal systems.

- MULTIBANDGAP ADVANCED PHOTOVOLTAICS - This technology appears to have the greatest potential for improving the performance of photovoltaic energy conversion by a nonincremental amount (30% efficiency).

- NEW HIGH-TEMPERATURE MATERIALS FOR THERMOELECTRIC CONVERTERS - Several materials have been proposed which have the potential of thermoelectric operation with sustained high efficiency at high temperatures. The gain would be equivalent to the relative gain in Carnot efficiencies achieved by raising the heat source temperature provided that increased thermal conductivity losses are minimized.

- NICKEL ELECTRODE IMPROVEMENT AND ELECTROLYTE INTERACTION - Proper understanding and improvement of electrode materials and structure has the potential of doubling the lifetime and specific power of nickel, hydrogen battery operation and

making it a significant successor to the current nickel, cadmium battery systems.

The second and third priority categories contain a total of 25 separate technologies spanning, for example, advanced photovoltaic cell research, batteries, thermionic converters, array and concentrator deployment schemes, novel radiators, materials development, beam power transmitters and receivers and dynamic thermal power conversion components. Details are included in Section 5. A separate search through these technologies was made to identify those areas in which little or no work is currently being supported for development. These included high-power systems development, high-temperature batteries, flywheel energy storage, power beaming, lightweight solar concentrators and high-temperature power-processing components. The long lead items in these areas serve to emphasize the need for starting programs in the areas of high-power systems development and materials and high-temperature concepts which often bridge the materials and high power systems requirements. The recommendations are completed by noting a definite insufficiency of data in several key areas with the potential for significant improvements and by suggesting appropriate studies to fill in these gaps.

There appears to be a multitude of good ideas for increasing the performance of space power systems. The Advanced Energetics Program has an excellent choice to work from and can have an important impact on space power systems of the future.

Section 2

TECHNOLOGY REVIEW AND ASSESSMENT

The thrust of advanced energy technology in space towards higher powers and more reliable, lighter weight systems already has its foundations in concepts that are under development now. Each of the main technology categories (e.g., sources, converters, storage, etc.) is reviewed below to determine the current state of the art and to establish benchmarks against which to judge future improvements. These benchmarks are based on the best performance of flight-tested components. New or advanced concepts must show a non-incremental improvement over the benchmark performance in order to be considered a significant advance over current technology. The theoretical limits and practical operating ranges of new and advanced technologies are also reviewed in those cases where sufficient data is available. Each technology subsection closes with recommendations of specific technical areas which should be pursued to advance the performance of space power systems.

2.1 Energy Sources and Collection

2.1.1 Introduction

This section describes the status of advanced technologies which are used to collect and concentrate solar energy for conversion to on-board power, and nuclear power technologies such as radioisotope sources and nuclear reactors. Basic energy source requirements in terms of absolute power needed and the form of delivery to the energy conversion unit (i.e., by thermal conduction, radiation, neutron transport, etc.) are described. Limits to the performance of advanced energy source technology currently in use or under development are estimated in order to establish benchmarks for comparing potential improvements in this area. Conventional technology in this area is limited to solar energy utilized by flat array solar collectors for photovoltaic cells and radioisotope nuclear power sources for planetary probes. Partially developed technology includes low concentration ratio collectors for photovoltaic conversion, high

concentration ratio solar concentrators for solar thermal power conversion, and nuclear fission reactors (solid, liquid, and gaseous fuels) for larger scale space power systems. The section concludes with an assessment of new and advanced technologies which offer substantial improvements over the performance benchmarks established for existing technologies.

Performance limits projected for developing technologies indicate that lightweight (500 g/m^2), low concentration ratio (~10), solar collectors for photovoltaic cells can be ready for flight testing in the near future as a natural evolution of current developments. Systems combining lower weights and higher concentration ratios are strongly needed in order to achieve the full advantages of gallium arsenide photovoltaic cells. Current technology for higher concentration ratio (500 to 1000), paraboloidal solar concentrators is limited to small (0.5 meter diameter or less) sizes in lightweight versions. At the intermediate scale, paraboloidal concentrators 6 meters in diameter with specific masses of 5000 g/m^2 have been built.(6) Scaling to larger sizes (i.e., up to 15 meters diameter) appears to result in specific masses of about 2500 g/m^2, at present. Therefore, to enable the use of higher power solar thermal energy conversion systems, much lighter weight solar concentrators scalable to large diameters must be obtained.

Solar thermal receivers are integrally related to solar concentrators for thermal power conversion. Current receiver developments, associated at present with terrestrial applications, suggests that specific weights of 0.2 kg/kW (of thermal power transferred) can be reached in a near-term program. Such receivers will have practical temperature limits of 1500 to 1800 ^{o}K due to the blackbody re-radiation occurring at higher temperatures and the subsequent loss in receiver efficiency. These devices can be scaled to larger sizes (i.e., Megawatts) but will need novel approaches to achieve higher temperatures at high receiver efficiencies.

Radioisotope heat sources currently produce approximately 480 Wth/kg; these devices are a maturing technology with no prospects for very large increases in specific power. These heat sources are highly reliable and have lifetimes on the order of 15 years using current designs where the

limits are not due to the source itself but rather to the converters. Thermal power is limited to roughly 2400 W per module. The potential to achieve higher powers and lower specific masses exists in the prodigious amount of development already invested in nuclear reactor technology for space. For example, the SPAR solid fuel UO_2/Molybdenum reactor concept under development at the Los Alamos National Scientific Laboratory has an unshielded specific power projected at 1200 Wth/kg, a factor of 2.5 greater than the radioisotope heat source specific power. These devices are being designed in modules on the order of 100 kWe, each with the potential to scale to approximately 1 MW(e) in size. The prospects for even higher specific powers are good but will require advanced concept development, probably in the gaseous fuel reactor area. The question of the kind and size of nuclear power sources that should be developed in NASA's programs is very much at issue and needs further clarification through comparative power systems studies (e.g., nuclear vs. solar) and through a careful risk and safety analysis. A recent NASA procurement has begun this process of evaluation.

2.1.2 Requirements

Energy sources capable of supplying power in the range of tens of kilowatts to several hundred kilowatts are needed for the class of missions currently under consideration by NASA. These can be divided into missions where solar energy is sufficient and those where nuclear power is a necessity. Solar energy conversion is effective from approximately 0.1 to 2 astronomical units (1 AU $\approx 1.6 \times 10^8$ km, i.e., the earth-sun distance). A variety of different solar conversion technologies will be needed to actually span this range of distance from the sun. Photovoltaic cells can be used over this range but are constrained to regions which are relatively free from strong charged particle bombardment. Frequent passage through the Van Allen belts and similar space plasma or solar storm plasmas rapidly degrade solar cell performance. Very close to the sun direct solar thermal power systems may be used if the radiators can view the cooler regions of space. High concentration ratio collectors will certainly be needed far from the sun to bring the intensity of the collected radiation up to a

usable level. Concentrators are also needed for high temperature solar thermal power systems and may be needed for more efficient, long-lived photovoltaic cell converters. Nuclear power systems appear attractive for missions far from the sun and have also been used because of their long life, high reliability characteristics. Nuclear power systems are also being considered as a possible alternative for orbit-raising missions where many passes through the Van Allen belts will be required.

2.1.3 Energy Sources

The status of current technology for solar collector/concentrators, solar thermal receivers, and nuclear energy sources is reviewed below. Flat plate collector arrays, the most common and best developed solar collector technology for spacecraft, are discussed first. These include flat panel and flexible roll-out array structures. The assessment of photovoltaic cells is deferred to Section 2.2. While early work on solar concentrators and receivers was carried out by NASA, the most recent developments are associated with DOE-sponsored research related to terrestrial power systems.

Nuclear sources have been under development since the 1950s for space power purposes. They offer very long life and very high integrated energy output per unit weight. A variety of nuclear systems have been pursued. Some of these have been dropped, while others appear promising but have not been carried to the application stage, and still others are either being applied or will be applied relatively soon.

2.1.3.1 Solar Collectors and Concentrators

Solar photovoltaic cell arrays have traditionally been flat arrays with no concentration of solar radiation. In contrast to photovoltaics mounted on a satellite's body, flat arrays provide continuous exposure to

the sun, with close to optimal angle of incidence. Generally, it is difficult to speak of the array without the photovoltaic cells because many of the structures integrate these two elements. However, materials, structures, and mode of deployment help to distinguish the different types of flat arrays. In many cases, the array is made in rigid panels which are unfolded in space. Other arrays consist of a flexible material which is deployed by unrolling it. The rigid panel structures generally provide more accurate orientation to the sun but tend to be heavier per unit area than the roll-out arrays. The roll-out arrays are lighter per unit area, but their performance can be degraded by poorer solar alignment. A variety of additional trade-offs ultimately governs which choice is used. In the past five years low concentration ratio (i.e., 2 to 10) arrays have been considered as a possible means for reducing the amount of semi-conductor material required for a given power output and for raising the efficiency of photovoltaic conversion. Actually, maximum efficiency often occurs at higher concentration ratios, but the attendant cell heating is harder to control and the system specific power deteriorates compared to lower concentration ratios. Also, higher concentration ratio collectors require greater pointing accuracy to maintain their advantages. A selection of photovoltaic concentrators adapted from a recent review article (7) is shown in Figure 2.1 to illustrate the diversity of concepts being considered. Some configurations also lend themselves to cell protection from high energy particle fluxes (e.g., case N, Casegrainian Light Cone), and others may be especially suitable for split spectrum photovoltaic arrays (e.g., Cases C, I, J, and N). Details on photovoltaic cell technology are presented in Section 2.2.

Larger solar concentrators have been constructed for space thermal power conversion systems which operate at elevated temperatures. Several of these schemes are shown in Figure 2.2 (a) and (b), suggesting a 14 meter diameter paraboloidal concentrator with 2400 g/m^2 specific mass which could be inflated and then rigidized with a quick setting foamed plastic backing.(8) A paraboloidal deployable (petalled) concentrator 9 meters in diameter was also constructed on the Sunflower project with a honeycomb sandwich construction, aluminum surface, and 2960 g/m^2 specific mass.(9) An

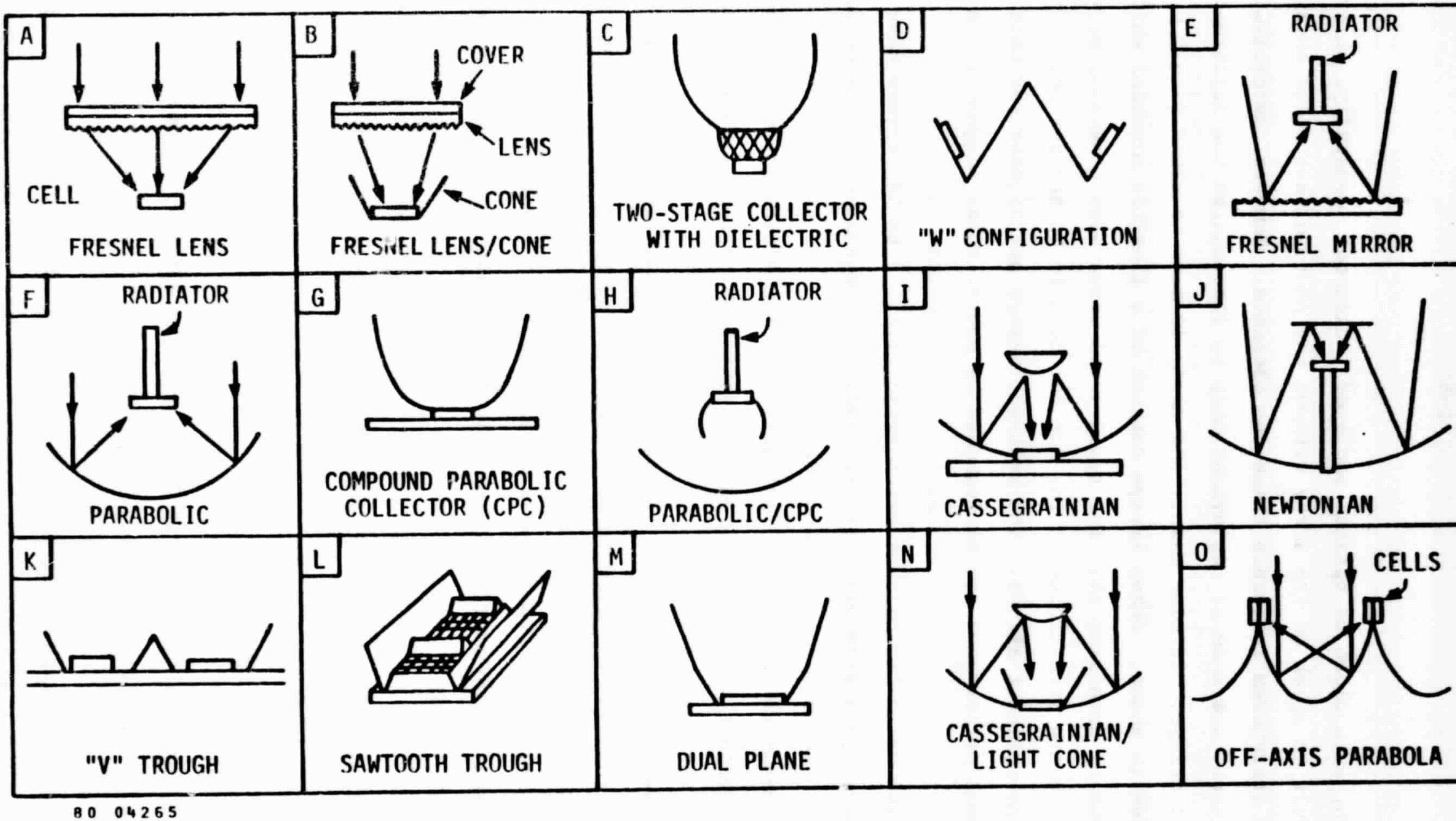

Figure 2.1. Concentrating Photovoltaics
(Adapted from Reference 7)

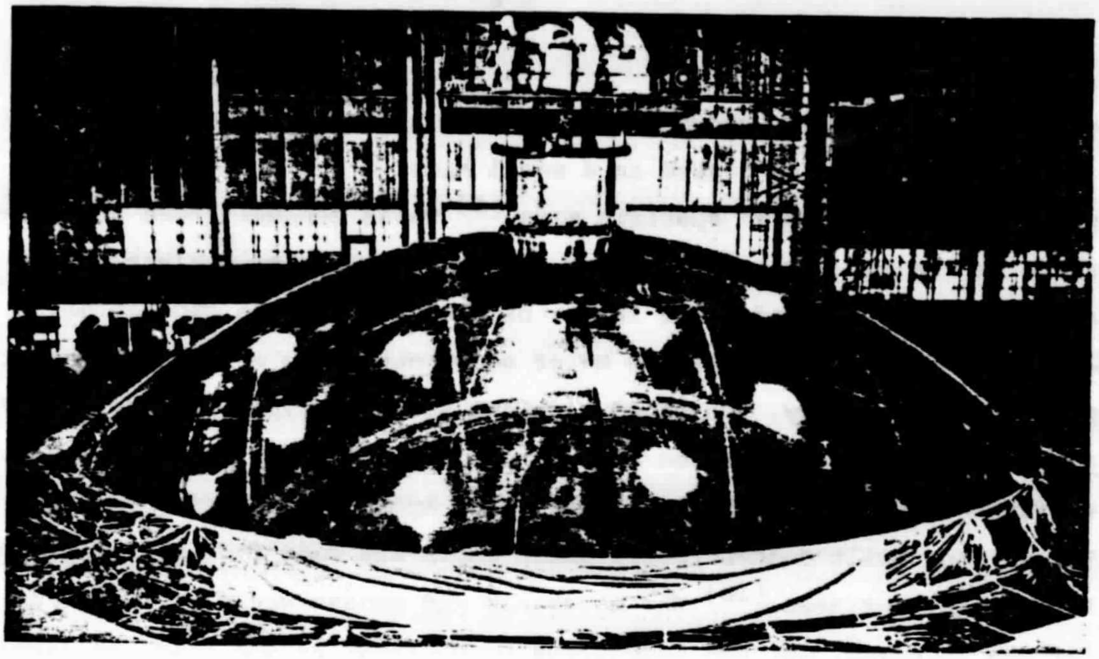

Figure 2.2 (a). Plastic Film Inflated to Paraboloidal Shape. (Reference 8)

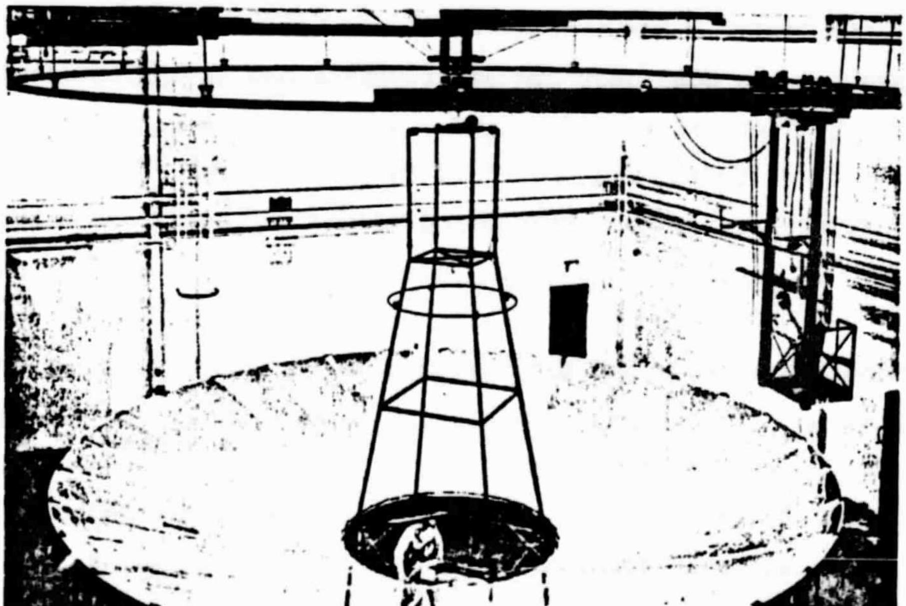

Figure 2.2 (b). Sunflower Concentrator, Deployed. (Reference 9)

alternative approach (shown in Figure 2.3) using a cone and column concentrator was also tested in a small size (1.5 m diameter) with projections of 500 g/m^2 specific mass.[8] These concentrators represent the state of the art for space systems even though neither one has been actually flight-tested. The larger of the two would be capable of delivering on the order of 200 kW of solar energy to a receiver assuming perfect reflectivity. Polished aluminum surfaces typically reflect 85 percent of visible radiation at near normal incidence; evaporated gold surfacing can improve the reflectivity to approximately 99.7 percent. Larger land-built concentrators exist which are made from silvered glass or thick metal surfaces.[10] The materials and masses would be inappropriate for use in space, but the technology of configuring and aligning larger surfaces in paraboloidal shapes has been established in principle.

2.1.3.2 Solar Thermal Receivers

Similarly, solar thermal receivers have been constructed for space. For example, the Sunflower project receiver had an approximately 50 cm diameter cylindrical cavity aperture with tubing wound around the cavity interior to carry the working fluid (Biphenyl - see Figure 2.4).[9] Larger cavity receivers are currently being tested at the Sandia Albuquerque solar thermal test facility.[11] These receivers, in the 1 to 5 MW class, are several meters in diameter, operate with steam or helium at temperatures of approximately 500 ^oC, and are designed for terrestrial power tower applications. A separate smaller, distributed power solar receiver research program is also in progress at Jet Propulsion Laboratories (JPL) where receiver sizes in the range of 10 to 100 kW are being investigated, which can reach peak temperatures in the range of 1200 ^oK to 1400 ^oK; examples of the higher temperature receiver concepts are shown in Figure 2.5 which utilize ceramic heating elements and, in some cases, windows to allow cavity pressurization.[12] Higher temperatures will require novel approaches to receiver technology. In particular, the temperature limits outlined above normally restrain thermal cycle efficiencies (e.g., Brayton cycle) to 35 percent or less when the heat rejection temperature is taken

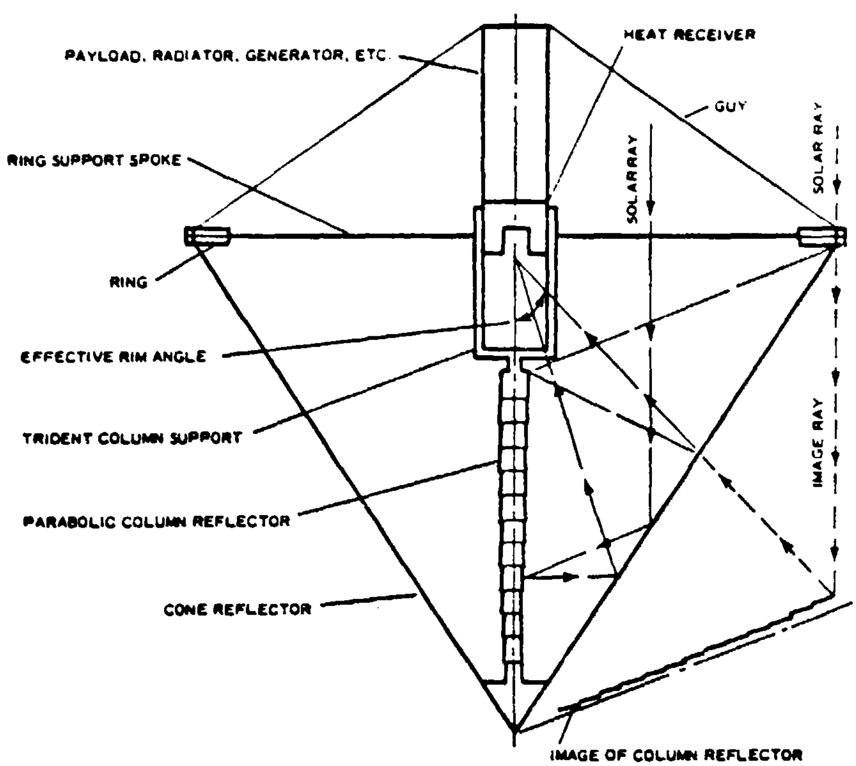

Figure 2.3. Cone-and-Column Concentrator Optics.
(Reference 8)

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Figure 2.4. Heat Receiver and Test Loop Installed on the Ten Foot Solar Concentrator. (Reference 9)

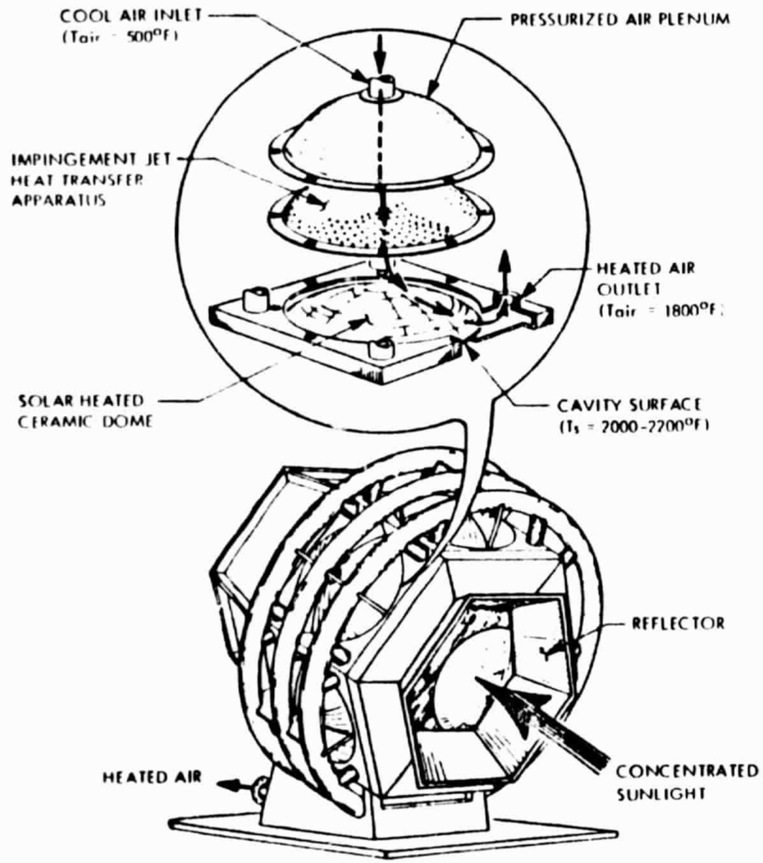
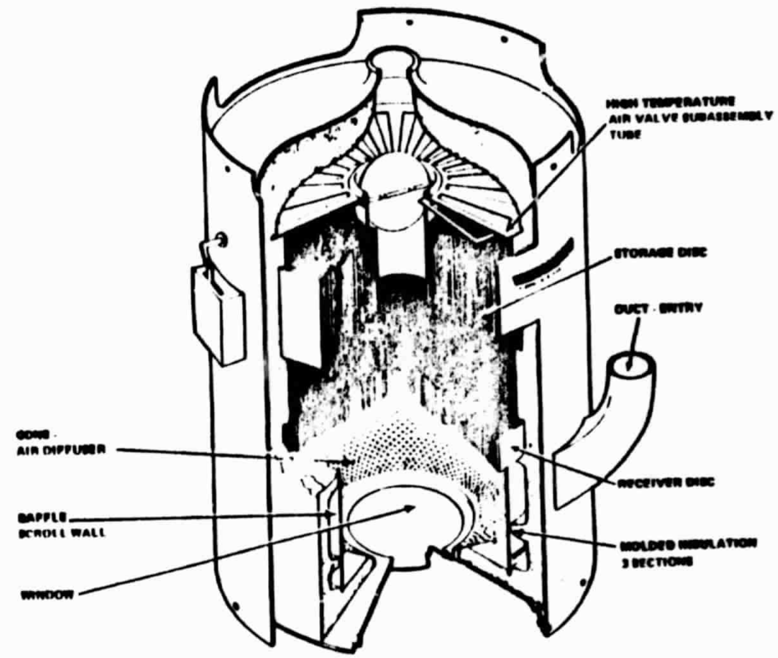


Figure 2.5 (a). Artist's Conception of a MIT/LL 1 MWth Ceramic Dome Receiver. (Reference 12)



(b) Section View of Sanders Receiver. (Reference 12)

into account. Thermal energy conversion is discussed in detail in Section 2.2.2.

2.1.3.3 Radioisotope Sources

Radioisotope sources have proven very successful. In many cases they offer substantial advantages over other energy sources and, in some cases (outer planetary missions), are the only viable choice. Table 2.1 summarizes existing and developmental radioisotope space power sources as of the early 1970s. The state of the art is represented by the Multi-Hundred Watt (MHW) radioisotope heat source used on the DOD LES-8 and -9 satellites and on NASA's Voyager missions. The MHW source produces 2400 Wth, weighs 21 kg, and typically operates at 1400 $^{\circ}$K.

Thermoelectric power conversion has been the main power generation method employed with radioisotope thermal generators (RTGs) giving efficiencies in the range of 5 to 7 percent and output powers of ~0.5 KW(e). Optimization of the RTG could probably increase efficiency up to ~10 percent and overall specific power of ~88 Wth/kg.[13-15]

While it is probable that radioisotope sources will continue to be used for space power, limitations on supply will constrain its future use to an amount not much more than presently used. The only practical isotope appears to be Pu^{238}, which must be made by expensive and difficult successive neutron captures from U^{235}; in fact, it is only realistic to produce Pu^{238} as a byproduct from other reactor operations. At ~10 percent power conversion efficiency, only 50 watts(e) of power capability is available per kg of Pu^{238}. It is doubtful that more than a few KW(th) of additional radioisotope power sources per year could ever be available for space purposes. While less developed as a radioisotope source, nuclide 244 Cm_2O_3 has roughly four times the power density of Pn-238 and might be somewhat more available.

Accordingly, future work in the area of radioisotope sources, although it can increase efficiency somewhat to make better use of the Pu^{238} heat source, cannot greatly expand either the capability of

Table 2.1

Historical Summary of Radioisotope Systems
(Reference 16)

Designation	Application	Contractor	Output (watts)	Design Life (yr)	Weight (lb)	Isotope Fuel	Remarks
SNAP-3A	Transit 4A-Navigation Satellite	Martin	2.7	5	5	Pu^{238}	Launched June 1961. Operating at undetermined lower power level
SNAP-3A	Transit 4B-Navigation Satellite	Martin	2.7	5	5	Pu^{238}	Launched Nov. 1961. Shutdown by power system failure June '62
	Navigation Satellite	Martin	25	5	27	Pu^{238}	Launched Sept. 1963. Operating at undisclosed lower power level
SNAP-9A	Navigation Satellite	Martin	25	5	27	Pu^{238}	Launched Dec. 1963. Operating at undisclosed lower power level
SNAP-9A	Navigation Satellite	Martin	25	5	27	Pu^{238}	Launched April 1964
SNAP-11	Lunar Surface Use	Martin	25	0.3	30	Cm^{242}	Developmental
SNAP-17A	Developmental	Martin	30	3-5	30	Sr^{90}	Developmental
SNAP-17B	Developmental	G.E.	30	3-5	30	Sr^{90}	Developmental
SNAP-19	Nimbus-B Weather Satellite	Martin	30	5	30	Pu^{238}	Launched April 1970
SNAP-27	Apollo Lunar Surface Exper. Pkg. (Alsep)	G.E.	50	1	40	Pu^{238}	Placed on lunar surface by Apollo 12 astronauts Nov. 1969
SNAP-29	Military	Martin	400	0.25	400	Po^{210}	Development terminated
Transit	Navigation Satellite	TRW	30	5	27	Pu^{238}	Under development
Pioneer	Space Probe	Teledyne	30	3	30	Pu^{238}	Under development
Multi-100 Watt RTG	Unmanned Scientific Missions	G.E.	100 to 200	12	50 to 100	Pu^{238}	Under development
Viking	Mars; Lander	-	35	2	30	Pu^{238}	In planning
LRHS	Manned Missions	-	25 kwt	-	-	Pu^{238}	Heat source for Brayton cycle PCS. In planning.

individual missions by large increases in power nor can it substantially increase the number of missions. In fact, if radioisotope generators were to be preferentially allocated for space military applications in the future, the amount of power available for NASA purposes could decrease.

2.1.3.4 Nuclear Reactor Sources

No such supply constraint applies to reactor based power sources. There is ample fuel to sustain many hundreds of megawatts of power generation in space at high efficiency and high specific power. A number of systems were under development for space nuclear electric and space nuclear propulsion, but were all cancelled about nine years ago. In general, the propulsion reactors could, in principle, also be used for electric generation by using the hot gas output in a turbine or MHD energy conversion system.

The SPAR Reactor

At present, the only space nuclear reactor still being developed is the SPAR reactor system at LASL.[17,18] SPAR will generate 100 KW(e) from a 1.2 MW(th) fast reactor (8.5 percent thermal efficiency) using thermoelectric converters. Heat is transferred from the ~1100 °C UO_2-Mo core by sodium vapor in Mo heat pipes to the TE converters. Reject heat is removed by a 500 °C space radiator with titanium-potassium heat pipes. Overall specific mass would be ~20 watts/lb or about an order of magnitude higher than RTGs. The design life of the SPAR reactor is 7 years, which would permit a wide variety of missions; increasing its lifetime to approximately 10 years would also allow outer planet exploration. Figure 2.6 shows an overall view of the baseline reactor, and Table 2.2 summarizes the operating parameters. Reactor size is very small (L/D ~1, D ~52 cm). Table 2.3 summarizes system mass parameters for a range of output powers from 10 to 100 KW(e) using the same basic reactor as structured for unmanned missions; manned missions will require substantially more shielding.

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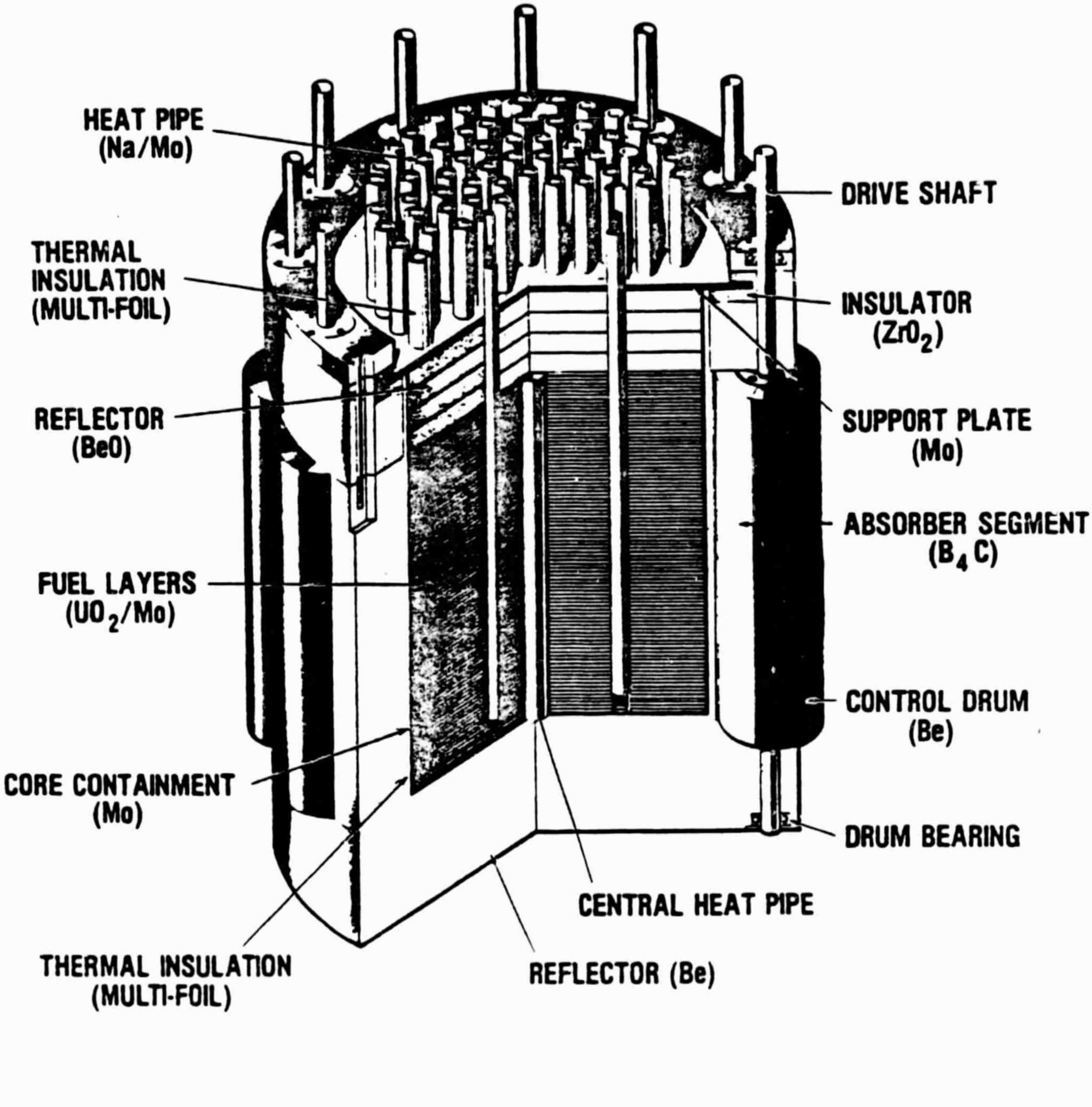

Figure 2.6. SPAR Layered-Core Reactor Design (Reference 17).

Table 2.2

(Reference 19)

SPAR REACTOR DESIGN PARAMETERS

Reactor power (kW_t)	1200
Core diameter (mm)	290
Core height (mm)	290
Core heat pipes	
Number	90
Temperature (K)	1400
Reactor diameter (mm)	520
Reactor height (mm)	500
Reactor mass (kg)	400

CORE HEAT PIPE PARAMETERS

Number	90
Design criterion	
MW/m^2 of vapor area	100
Heat pipe ID (mm)	13
Power per heat pipe (kW)	13.3
Heat pipe o.d. (mm)	15.7
Maximum axial ΔT (K)	1
Radial input heat flux (MW/m^3)	1.1

Table 2.3

Operating Parameters of SPAR Thermoelectric Power Plant with Seven Year Lifetime (Reference 20)

	Power (kW_e)		
	10	50	100
Reactor power (kW_t)	110	550	1100
Core heat pipe temperature (K)	1400	1400	1400
Fuel swelling (%)	1	2	3
Burnup fraction - ^{235}U (%)	1	2	4
Thermoelectric efficiency (%)	9	9	9
Radiator temperature (K)	775	775	775
Radiator power (kW_t)	100	500	1010
Power plant mass (kg)	810	1255	1775
Reactor	400	400	400
Shield	255	335	380
Thermoelectric converter	30	140	285
Radiator	50	255	530
Structure	75	115	160

The present SPAR program is developing the technology base needed to build a ground based prototype through both analytical and experimental investigations. Construction of such a prototype could be initiated in 3 to 4 years, depending on results from the present SPAR program which is funded at a level of 2 million dollars a year.

Current experimental efforts center on fabrication and testing of Mo-Na heat pipes for the reactor core, Ti-K heat pipes for the radiator thermoelectric modules, and fuel elements for inpile radiation tests. Although still in the initial stages of development, all components built and tested so far have performed satisfactorily.

The neutronic design of the SPAR reactor has been checked by construction of a critical assembly; theoretical and experimental K_{eff} values agreed to within 1 percent.

Design studies of a Brayton cycle with turbine inlet temperatures ranging from 925 to 1475 ^{o}K for use with advanced nuclear reactors have been carried out.[21] Specific Brayton cycle studies for the SPAR reactor have been carried out[22] which would require higher reactor temperatures on the order of ~1300 ^{o}C with turbine inlet temperatures of ~1200 ^{o}C. Thermal efficiency would be considerably larger than that of a thermoelectric conversion system, i.e., ~25 percent versus ~8 percent.

If successful, the SPAR project will allow space nuclear power systems in the range of ~50 KW(e) to ~1 MW(e), depending on reactor size and power conversion method. It is doubtful that the SPAR technology can be scaled to much larger sizes because of heat transport limits in the Mo-Na heat pipes, as well as size limits relating to reflector control in fast reactor systems.

Liquid Metal Cooled Solid Fuel Reactors

Extensive work was carried out by Pratt & Whitney as well as Atomics International, NASA-Lewis, and Oak Ridge National Laboratory during the 1950s and 1960s on liquid metal cooled fast reactors for space applications.[23-25] Potassium turbines, thermionics, and two phase liquid

metal MHD were the main power conversion options investigated. Other options considered at that time included mercury Rankine, Brayton cycles, and thermo-electric concepts.[24,25] Projected thermal efficiencies ranged from ~5 to ~25 percent, depending on the option chosen.

In the SNAP-50 reactor, lithium was examined as the primary reactor coolant at a temperature of ~1100 °C for operating systems. Refractory metal piping (e.g., niobium, molybdenum) was required for high temperature strength and corrosion resistance. Under these conditions the reactor/power conversion system had good corrosion resistance. Power levels of 500 KW(e) were chosen as a first generation system, although ultimately the reactor could be scaled to much higher power levels because of the excellent heat removal capability of pumped liquid lithium. Power levels in the multi-megawatt level appeared achievable. The program was canceled for lack of interest in missions capable of using the SNAP-50 system.

Other lower temperature liquid metal cooled reactor development work was carried out on the SNAP-8 and SNAP-10 systems by Atomics International.[16,26] These were U-ZrH thermal reactors cooled by NaK eutectic, with a maximum coolant temperature of ~700 °C. Various conversion options were developed, including thermoelectrics and a mercury Rankine turbine cycle. Table 2.4 summarizes the SNAP reactors developed during the program. SNAP-8 parameters were 600 KW(th) and 35 KW(e) output (6 percent efficiency). A SNAP-10A system was launched into orbit and performed satisfactorily for 43 days at 40 KW(th) and 500 watts(e) using thermoelectric conversion until a malfunction in the power plant's voltage regulator caused reactor shutdown. The SNAP-8 program was stopped in 1972 during the general cancellation of the space program.

Gas Cooled Solid Fuel Reactors

The NERVA program[27-29] developed and succesfully ground tested a substantial number of high power hydrogen cooled, solid UC_2-graphite core reactors during the late 1950s to early 1970s. Figure 2.7 shows the 3/4 inch hexagonal fuel element designed by Westinghouse Astronuclear

Table 2.4

SNAP Reactor Test Experience
(Reference 16)

	SNAP EXPERIMENTAL REACTOR (SER)	SNAP DEVELOPMENTAL REACTOR (SDR)	SNAP 8 EXPERIMENTAL REACTOR (S8ER)	SNAP 10A FLIGHT SYSTEM (FS-3)	SNAP 10A FLIGHT SYSTEM (FS-4)	SNAP 8 DEVELOPMENTAL REACTOR (S8DR)
Critical	September 1959	April 1961	May 1963	January 1965	April 1965	June 1968
Shutdown	December 1960	December 1962	April 1965	March 1966	May 1965	December 1969
Thermal Power	50 kWt	65 kWt	600 kWt	38 kWt	43 kWt	600-1000 kWt
Thermal Energy	225,000 kWt/hr	273,000 kWt/hr	5.1×10^6 kWt/hr	382,944 kWt/hr	41,000 kWt/hr	4.3×10^6 kWt/hr
Electric Power	-	-	-	402 Watts	560 Watts	-
Electric Energy	-	-	-	4028 kW/hr	574 kW/hr	-
Time at Power and Temperature	1800 hr at 1200 °F 3500 hr above 900 °F	2800 hr at 1200 °F 7700 hr above 900 °F	1 yr at 1300 °F 400-600 kWt	10,005 hr (417 days)	43 days	7023 hr at 1200 °F 600-1000 kWt

Laboratory for use in NERVA. The overall core assembly showing fuel elements, central rods, reflector, and flow arrangement is shown in Figure 2.8. The NERVA reactor was aimed at space nuclear propulsion using H_2 at relatively high specific impulse (760 seconds). Although successful in ground tests, the lack of a definite mission led to the cancellation of the program in the early 1970s.

With some relatively simple modifications, NERVA technology could be applied to the generation of large amounts of electric power in space using either MHD, high temperature turbine, or thermionic conversion systems.

The NERVA system was H_2 cooled with design gas exit temperatures of 2100 ^oC. Projected operational lifetime was 10 hours, limited by chemical reactions of the H_2 coolant with the graphite fuel element. These were coated with carbide to reduce the erosion rate. At the end of operational life most (>99%) of the fuel would still remain, however. Design conditions are listed in Table 2.5.

For electric power generation a closed cycle operation with inert gas coolant (e.g., helium) would be used. For example, the 710 reactor was specifically designed for inert gas, closed cycle power generation by GE-Evandale. Under these conditions and somewhat lower temperature operation (e.g., ~2000 ^oC), fuel life should be very long (e.g., years). Since an electric power version of the NERVA system would, in general, be considerably lower power and operate in a CW or long pulse mode, many of the design problems in the NERVA propulsion application would be avoided.

Design power was 1500 MW(th) at a reactor weight of ~15,000 lbs, corresponding to a specific power of 100 KW(th)/lb. With a 20 percent conversion efficiency, this corresponds to a reactor specific power of 20 KW(e)/lb. Since reactor weight will decrease only slightly with power level, the specific power of derated systems would tend to go as $(\text{power})^{-1}$.

Cumulative test time for the various reactor engines tested (NRX series, XECF, and XE,KIWI series) was 15 hours at powers above 1 MW and 4 hours at high power. During early development, problems with flow induced

- SUSTAIN CONTROLLED NUCLEAR HEAT GENERATION

  PYROCARBON COATED UC_2 FUEL BEADS DISPERSED THROUGH AXM GRAPHITE MATRIX (530 MG/CC MAXIMUM FUEL LOADING)

  UC IN COMPOSITE WITH ZrC AND GRAPHITE (700 MG/CC MAXIMUM FUEL LOADING)

- LIMIT TOTAL REACTIVITY LOSS TO $1.00 AT END OF LIFE

  CARBIDE COATING OF FLOW CHANNELS

- AFFORD HEAT TRANSFER FROM FUEL ELEMENT TO H_2 PROPELLANT

  19 FLOW CHANNELS IN EACH 3/4 INCH HEX, x 52 INCH LONG FUEL ELEMENT

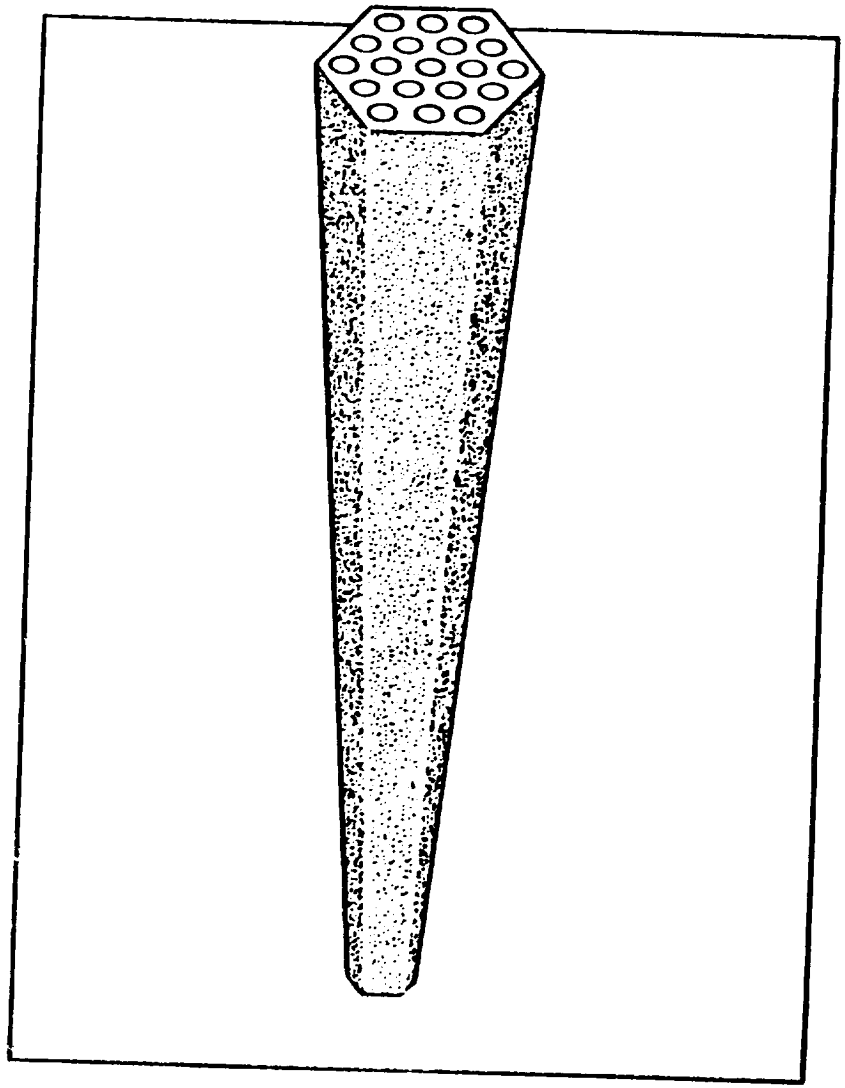

Figure 2.7. NERVA Reactor Fuel Elements (Reference 27).

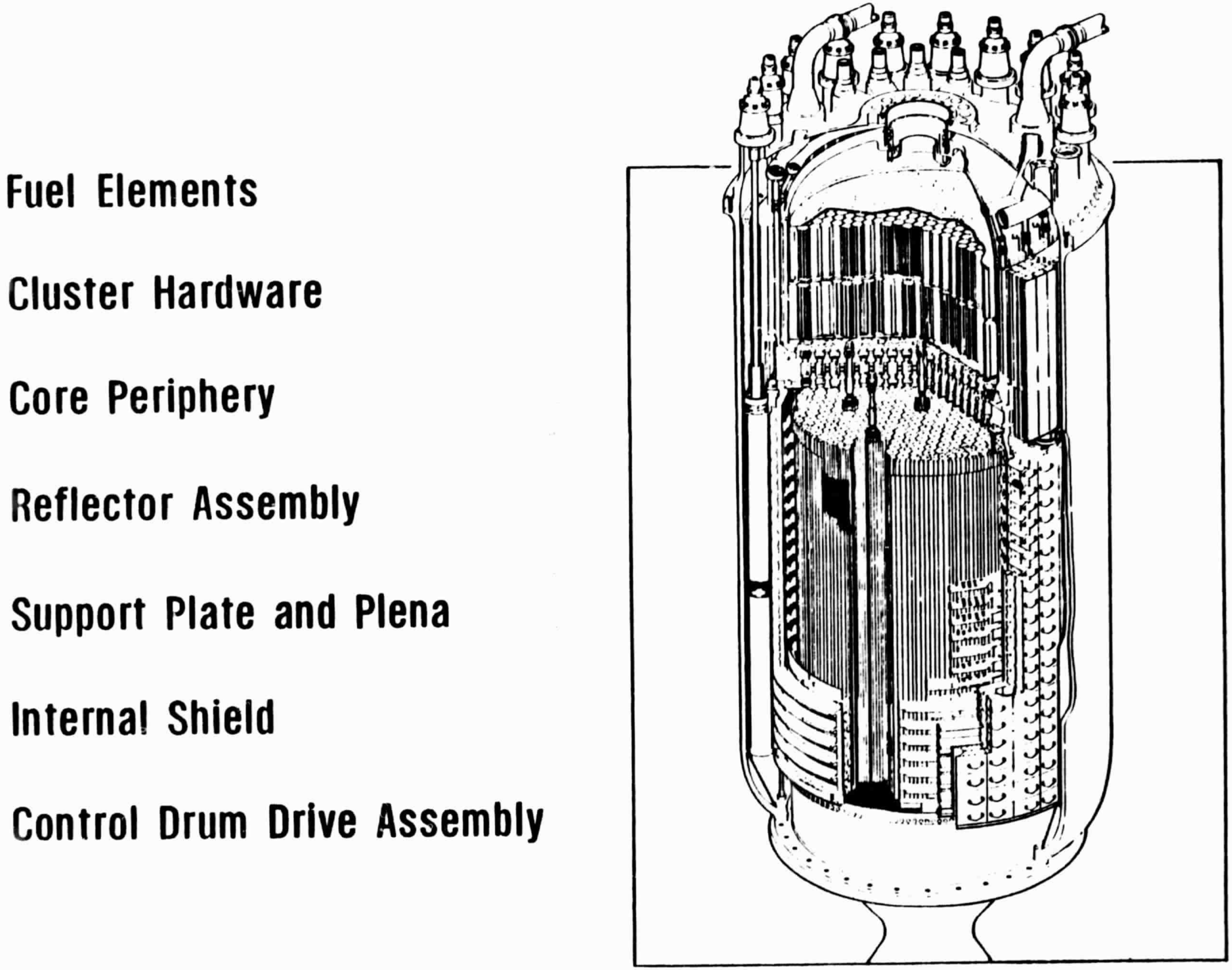

Figure 2.8. Overall Core Assembly for the NERVA Nuclear Space Power System (Reference 27).

Table 2.5

Design Conditions and Features
of the NERVA Reactor
(Reference 27)

FLOW DELIVERED TO NOZZLE	91.2 LB/SEC
TEMPERATURE DELIVERED TO NOZZLE	4250°R
STRUCTURAL SUPPORT COOLANT FLOW RANGE (NOMINAL)	7.1 TO 14.4 LB/SEC
POWER GENERATION	
THERMAL	1507 MW TOTAL
REFLECTOR	17.7 MW
SSCA	17.6 MW
SHIELD	1.6 MW
CORE	1470.0 MW
PRESSURE LOSS (REFLECTOR IN TO CHAMBER IN)	685 PSI
TOTAL FUEL LOADING	
GRAPHITE	275 KG
COMPOSITE	333 KG
NUMBER OF FUEL ELEMENTS	1878
REACTIVITY CONTROL	18 DRUMS ADJUSTABLE IN CORE HYDROGEN
TOTAL NSS WEIGHT OBJECTIVE (COMPOSITE FUELED CORE)	14, 957 LB

mechanical vibration were encountered. These were solved, and subsequent tests showed that NERVA engines could be repeatedly started and stopped without damage from a cold condition. Full design temperatures and powers were achieved on a number of occasions. Figure 2.9 summarizes reactor and engine system tests through the end of 1969.

Because of thermal shock considerations in the relatively large fuel elements, temperature ramp rates (up and down) were limited to a maximum of ~80 K/sec. This would not be a restriction for CW or long pulse electric power generation but could be a limitation for rapid pulse power applications.

Rotating Fluidized Bed Reactors

A second generation, higher performance reactor was under development as a possible eventual successor to the NERVA engine. In this reactor, the Rotating Bed Reactor (RBR),[30,31] the nuclear fuel was in the form of fine particulates several hundred microns in diameter contained in a rotating (~1000 rpm) porous metallic cylinder. Coolant gas was admitted through the walls of the cylinder, heated by contact with the fluidized fuel, and passed out through a nozzle at the bottom of the cylinder. Reactor control was by means of control absorber drums in the external moderator/reflector (graphite or beryllium). Figure 2.10 shows an overall view of the RBR with outer diameter equal to ~1 meter.

The RBR projected substantially higher operational temperatures (up to ~2700 ^{o}C), a lighter, more compact reactor [~1 m^3 for a power output of ~1000 to 2000 MW(th)], and absence from structural and thermal shock problems. Only the fuel was hot - all structural components were cold, and the small particulate nature of the fuel virtually eliminated thermal shock problems.

Non-nuclear flow, hydrodynamic, and heat transfer tests were carried out on a half scale RBR which established its basic feasibility. Critical assembly tests on cavity moderated reactors demonstrated that the projected nuclear performance could be achieved. Figure 2.11 shows the test

Reactor and Engine System Cumulative Test Time 1964-1969

KIWI-B4D (1 POWER TEST)	MAY 1964
KIWI-B4E (2 POWER TESTS)	AUGUST-SEPTEMBER 1964
NRX-A2 (2 POWER TESTS)	SEPTEMBER-OCTOBER 1964
KIWI-TNT	JANUARY 1965
NRX-A3 (3 POWER TESTS)	APRIL-MAY 1965
PHOEBUS-1A (1 POWER TEST)	JUNE 1965
NRX/EST (10 STARTS)	DEC 1965-MARCH 1966
NRX-A5 (2 POWER TESTS)	JUNE 1966
PHOEBUS-1B (1 POWER TEST)	FEBRUARY 1967
PHOEBUS-2 COLD FLOW TESTS	JULY-AUGUST 1967
NRX-A6 (1 POWER TEST)	DEC 1967
XECF (COLD FLOW)	FEBRUARY-APRIL 1968
PHOEBUS-2A (3 POWER TESTS)	JUNE-JULY 1968
PEWEE-1 (2 POWER TESTS)	NOV-DEC 1968
XE (28 STARTS)	DEC 1968-AUG 1969

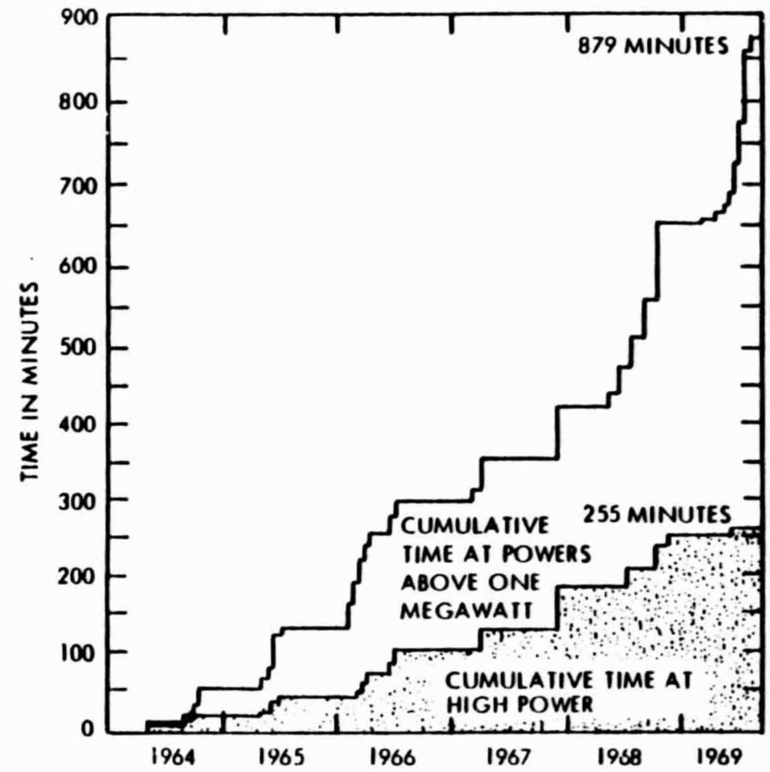

Figure 2.9. NERVA Test Experience (Reference 27).

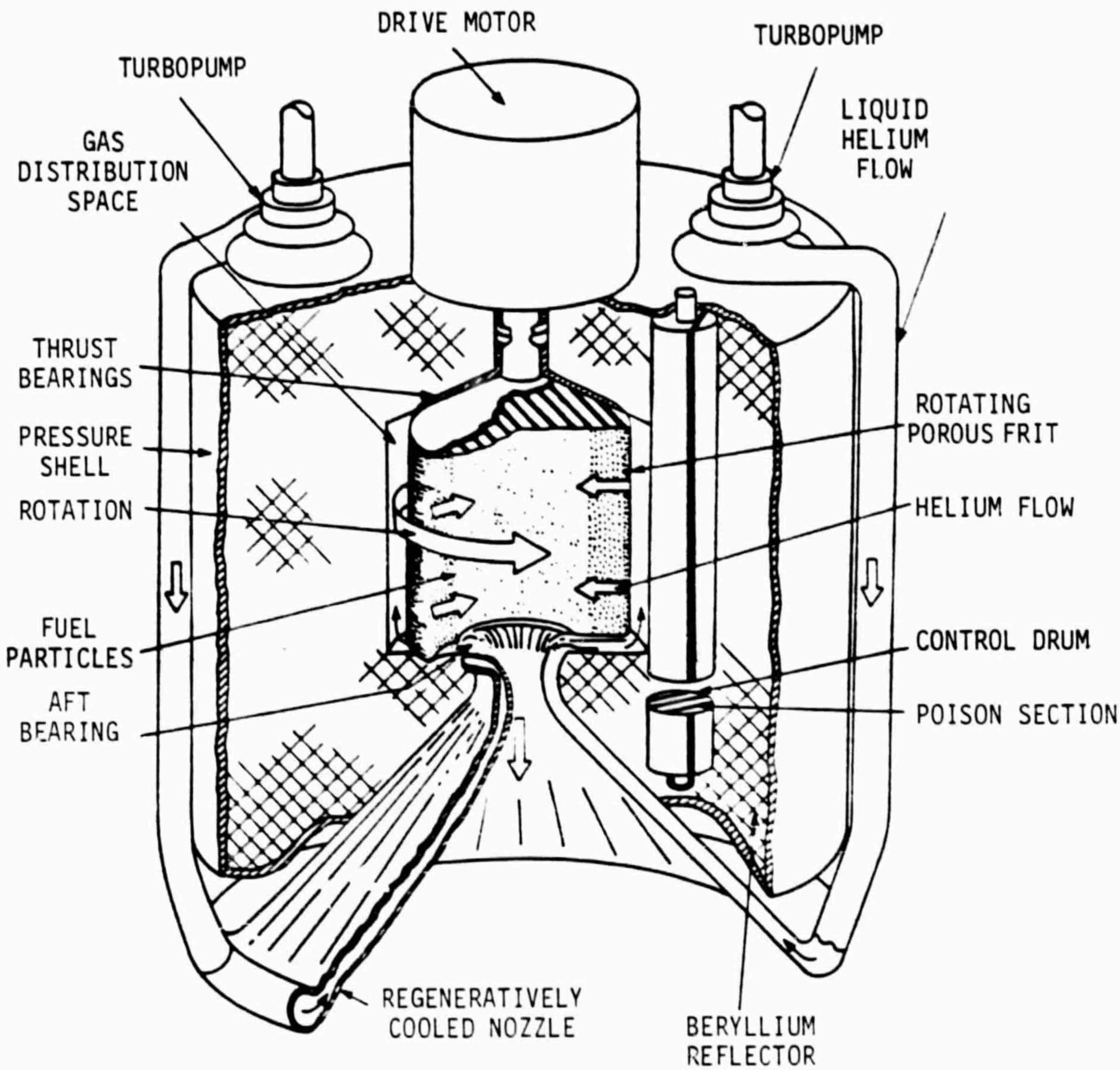

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Figure 2.10. Rotating Fluidized Bed Rocket Engine (Reference 30).

arrangement used for high speed movies and stills; the fully fluidized, stable bed was run at 1000 g. Pressure drops through the settling and fluidized beds were measured and found to agree with the theoretical predictions. In the fluidized state, pressure drop equals the bed mass times the effective centripetal acceleration. Particle motions were observed to be relatively smooth and gentle in the fluidized state.

Work on the RBR stopped along with all other work on the space nuclear propulsion program when it was canceled in the early 1970s. For high electric power generation applications in space, the RBR, together with the NERVA system, would be the leading contenders.

Liquid Fuel Nuclear Reactors

The liquid fuel nuclear reactor was proposed as a concept for space applications but not carried beyond that stage. There appear to be no significant advantages to liquid fuel and a number of major disadvantages. Although a number of liquid fuel reactors have been successfully operated (e.g., LAMPRE), the coolant temperatures achievable if liquid fuel is contained in tubes are relatively low due to corrosion limitations. Solid fuel reactors can achieve higher coolant temperatures more reliably. Reactors utilizing direct contact of a molten nuclear fuel with a gas coolant have been proposed; however, the mobility of the fuel poses severe problems of reactivity control and fuel loss.

Gas Fuel Nuclear Reactors

A number of concepts were proposed for a gas fueled nuclear reactor for space propulsion, and extensive tests were carried out on two mainline approaches - the confined vortex and the "nuclear light bulb."

A gas core reactor would permit considerably higher operating temperatures than the NERVA engine (10,000 K vs. 2400) and much higher specific impulses. Critical tests of cavity moderated assemblies (with both U foils as stand-ins and UF_6) have demonstrated that reactors can be operated with relatively low (~10 kg U^{235}) fissile masses.

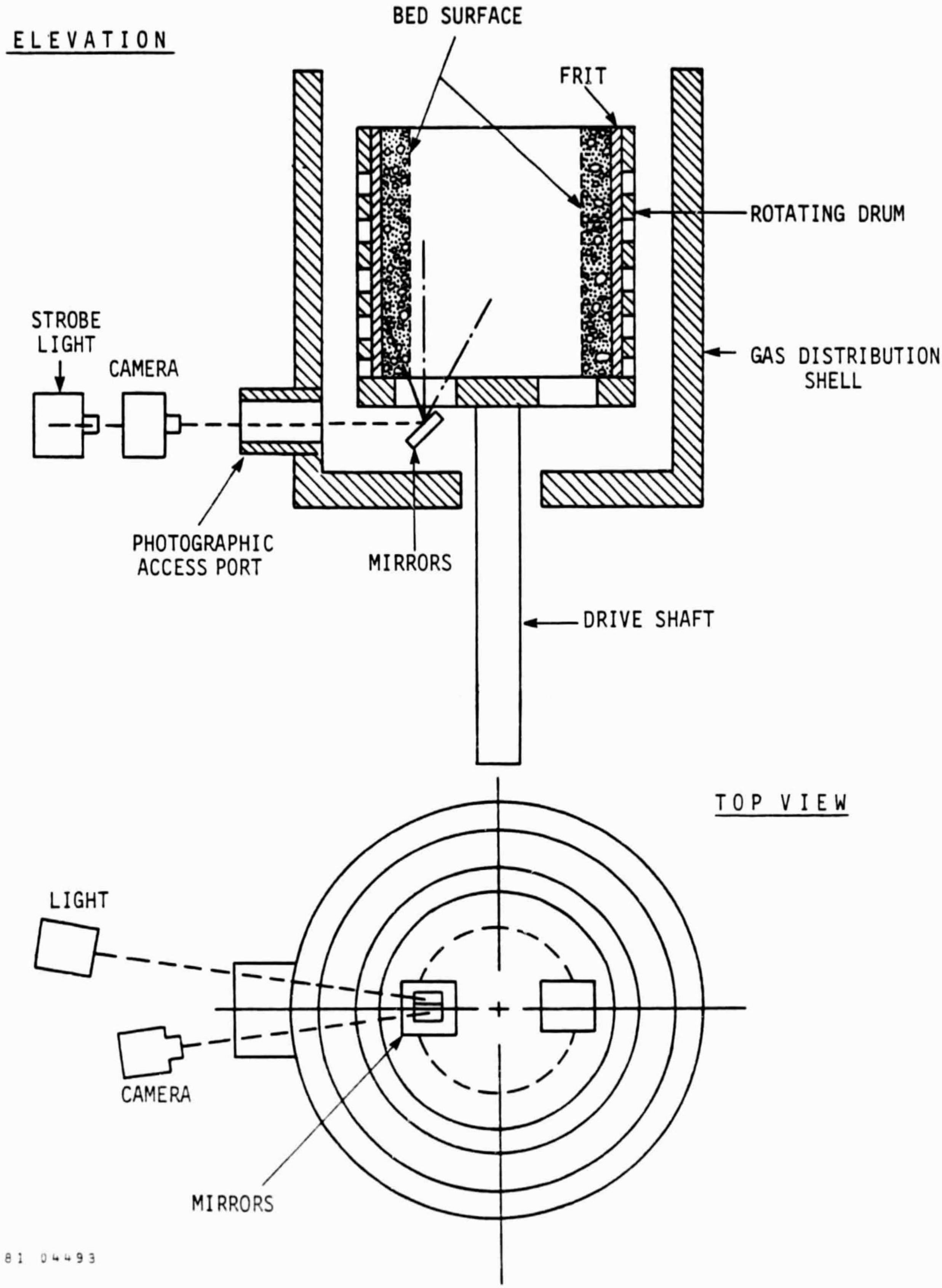

Figure 2.11. Elevation and Top View of Rotating Bed Reactor Experiments. (Reference 30)

Experiments with various types of confined vortex flows were not able to achieve the required H_2/U^{235} separation to permit a practical system. Turbulent diffusion at the interface between the two gases always resulted in excessive mixing. Typical containment parameters achieved were on the order of 10 (uranium residence time in the cavity divided by H_2 propellant residence time), while containment parameters of $\sim 10^3$ would be required for a practical propulsion reactor.

The nuclear light bulb concept separated the H_2 propellant and cerasium fuel with a thin transparent wall (silica or BeO) cooled by an auxiliary stream (e.g., neon). The containment problem appears solved, but major materials and thermal-hydraulic problems associated with maintaining the transparent wall against uranium condensation and excessive energy transport (both convective and radiative) are introduced. For these reasons the nuclear light bulb concept was canceled after substantial effort was invested in it.

Gas core reactors could be used for space nuclear electric generation but appear to have no significant advantage over solid fuel reactors, either in terms of overall weight or higher efficiency, and they possess substantial disadvantages related to their severe materials problems.

If the working fluid was separated from the fuel, we would be limited to the temperatures associated with corrosive interactions of the gaseous uranium (metal or UF_6) with the coolant tubes. In general, these would be substantially less than those with inert gas cooled solids or sodium cooled systems. If the uranium gas fuel were used in a direct power conversion system (e.g., conventional or pulsed MHD), severe gas circulation problems would be introduced together with materials problems relating to compressors, etc. Nuclear control of such systems would also be difficult. Finally, in general, MHD efficiencies would not appear to be significantly larger than those of inert gas cooled solid fuel systems, since the working fluid in gas core reactors, while hotter, is not as good for MHD cycles. It needs higher temperatures to be ionized, and generally

has poorer electrical conductivity due to higher electron-neutral scattering cross-sections.

2.1.4 Limits to Present Technology

Present solar concentrator technology is limited by both physics and engineering constraints. Sunlight can be concentrated no more than a factor of 45,370 in three dimensions; higher concentration ratios would permit focal point temperatures to exceed the blackbody source temperature of the sun which would violate basic thermodynamic principles.[32] In two dimensions (i.e., cylindrical parabolic concentrators) the limiting concentration ratio is approximately 213. These limits are indicated in Figure 2.12 which illustrates the limiting concentration ratio which can ideally be achieved from the sun for various concentrator geometries. The use of secondary reconcentrating mirrors placed about the receiver aperture is technically capable of raising the paraboloidal concentration ratio to the 3-D limit,[32] although this has not yet been established by experiment, to the author's best knowledge. Actual concentration ratios achieved by land based paraboloidal receivers[33] are shown in Figure 2.13, where the ratio α/ε of the receiver absorption coefficient to the emission coefficient is shown as a free parameter. Clearly, the peak temperature achievable in the receiver is a strong function of α/ε as well as the concentration ratio. In any practical concentrator the focal point intensity can be approximated by a Gaussian distribution. In particular, large size paraboloidal concentrators in space will most probably be constructed from a large number of flat facets which are individually aimed. Figure 2.14 shows the practical limits to concentration ratio associated with faceted receivers.[34] The larger number of facets the higher the concentration ratio up to a point where the number of facets becomes impracticably large. The impact of the resulting Gaussian distribution is that any receiver with finite aperture cuts off part of the incident intensity. However, as the aperture is reduced, the reradiation loss also decreases. Therefore, a maximum of *net* solar power received [= (incident intensity - reradiated intensity) x aperture area] occurs for an intermediate aperture size. This limit on receiver performance is

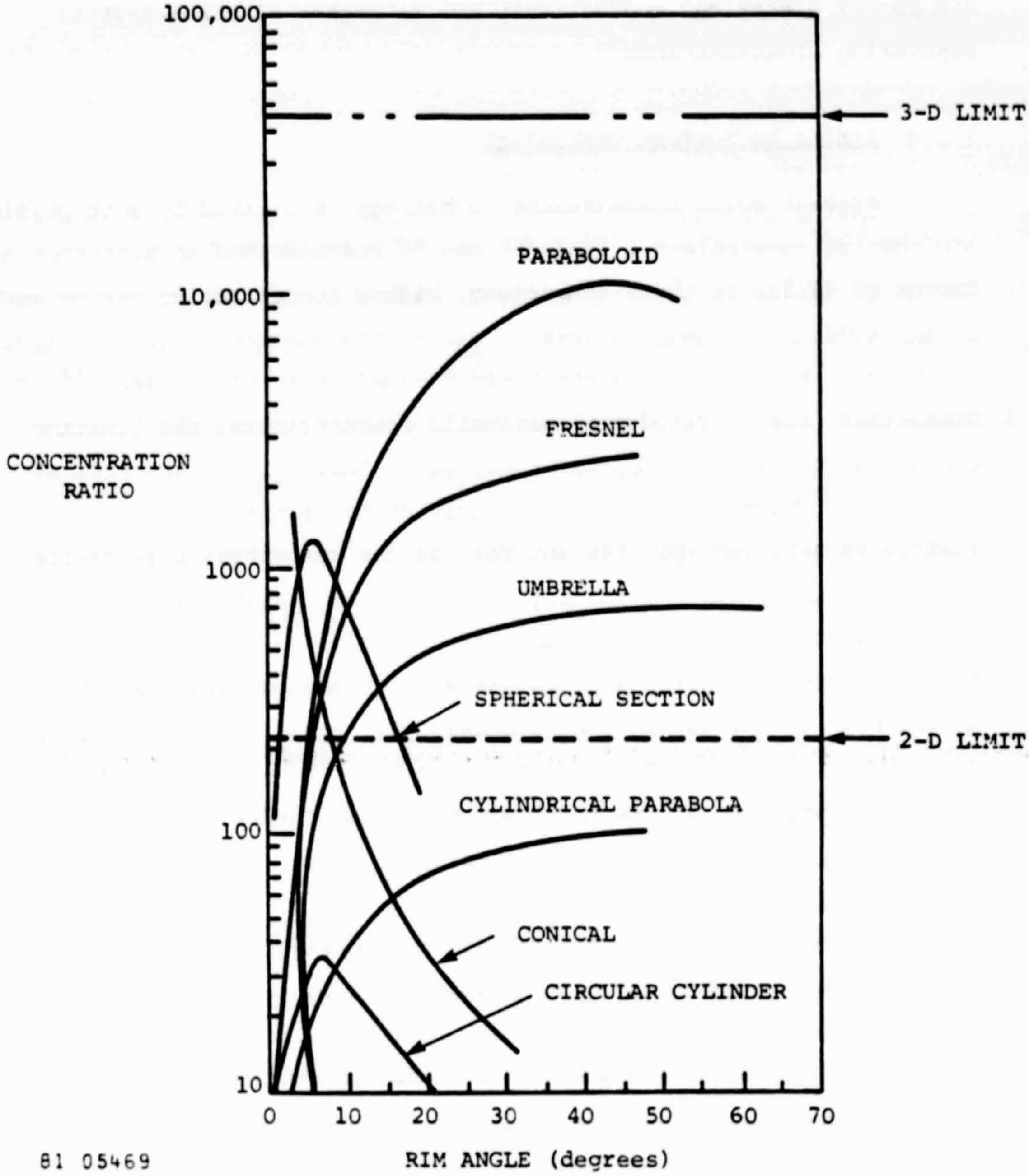

Figure 2.12. Concentration Ratio for Various Geometries.
(Adapted from References 32 and 36)

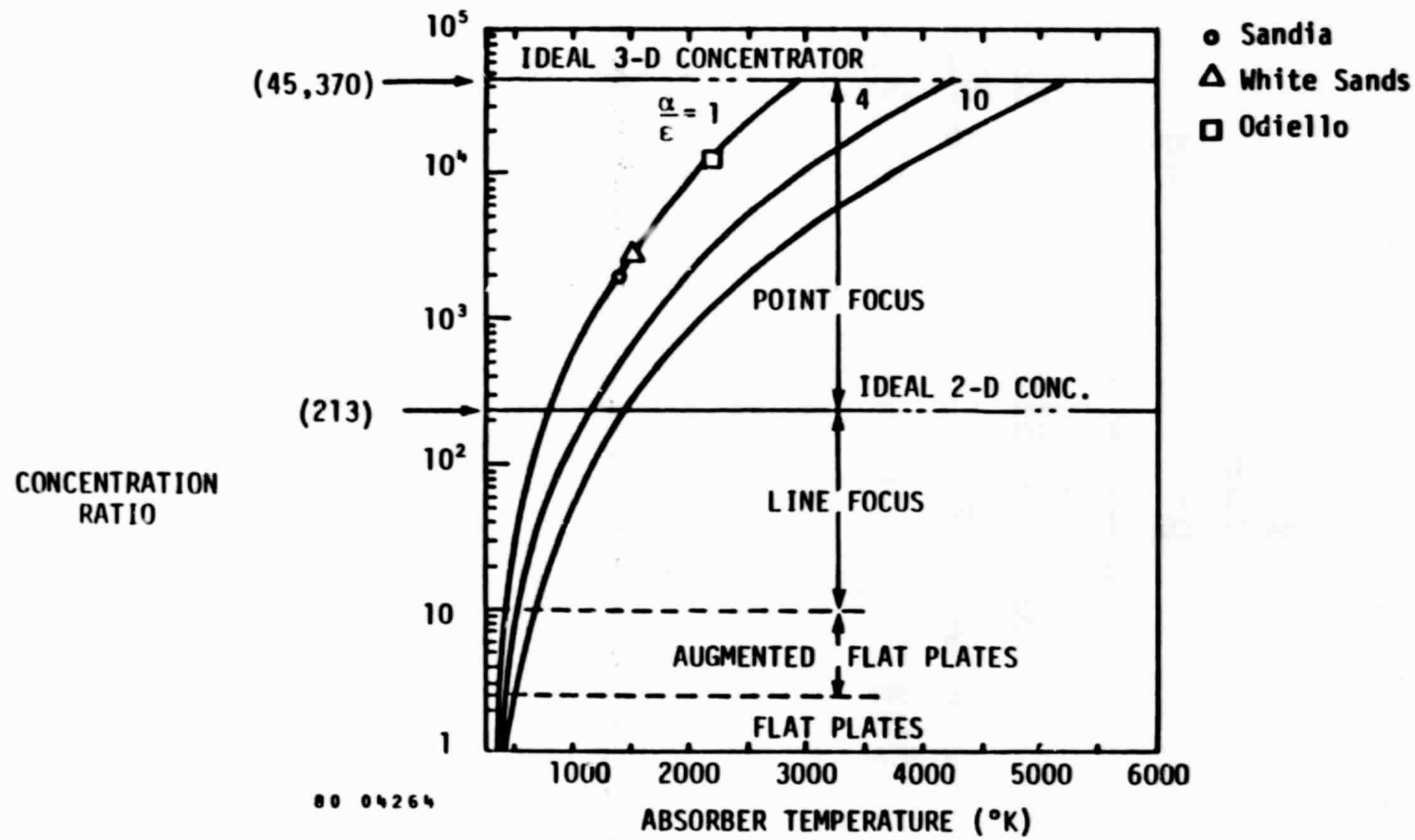

Figure 2.13. Solar Concentration Ratio versus Absorber Temperature.

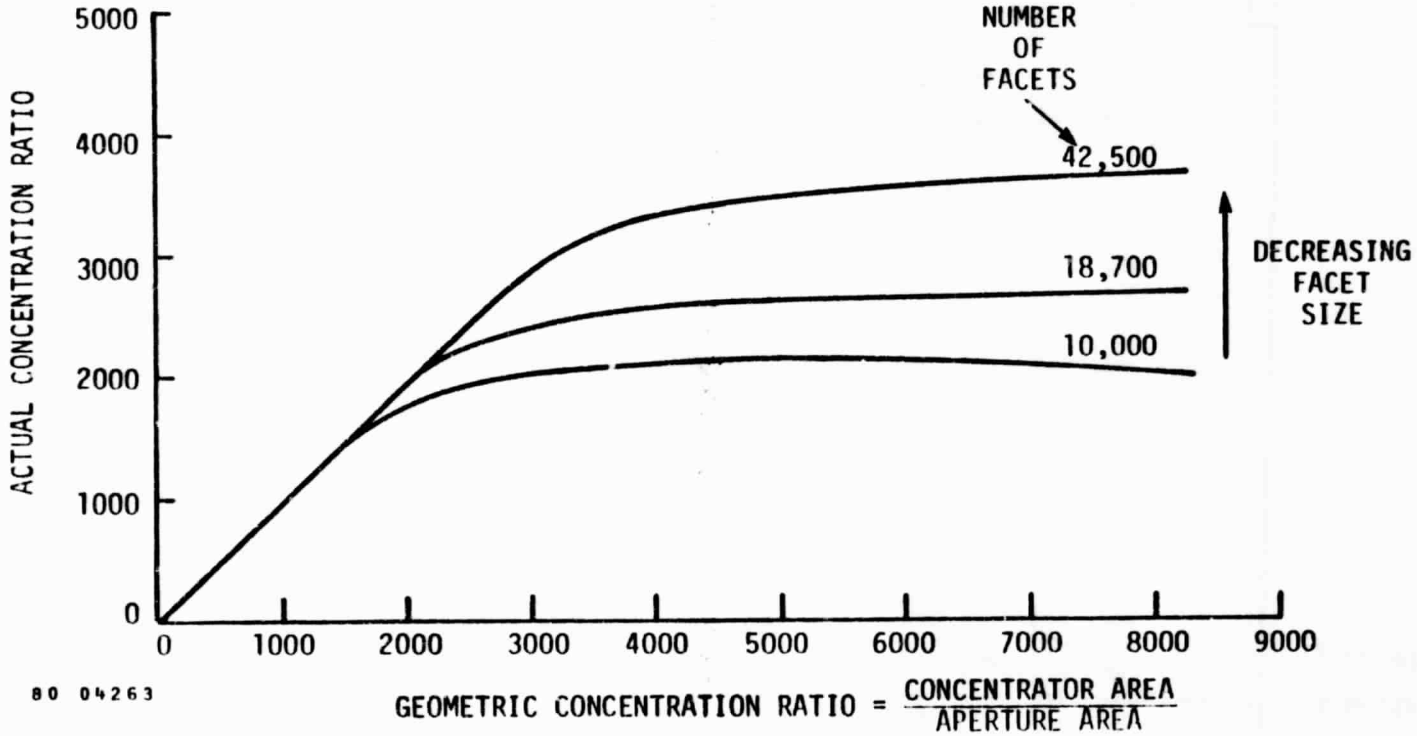

Figure 2.14. Actual Concentration Ratios Achievable with Faceted Paraboloidal Concentrators (60° Rim Angle (Reference 34).

illustrated in Figure 2.15.(35) The only way to surpass these limits is to achieve an effective reduction in reradiation temperature or emissivity. Figure 2.15 suggests that temperatures much above 1500 °K cannot be treated efficiently with present receiver and concentrator technology.

Limits to current nuclear source technology also derive from fundamental physical and engineering constraints which pertain to the half life of the source and the energetics of the radioactive decay mechanisms involved in the case of isotopes, and to the degree of criticality and supporting coolant systems in the case of nuclear reactors. Radioisotopes are also somewhat limited in supply. As noted earlier, Pu^{238} is limited to 500 W(th)/kg. In contrast, the power density of reactor sources can be considerably higher . For example, the SPAR reactor is designed for 3000 W(th)/kg of reactor mass with output temperatures as high as 1300 °C in the range of 500 kW(th) to 10 MW(th). The SNAP-50 series of liquid metal cooled reactors was designed for 2000 W(th)/kg of reactor mass with output temperatures as high as 1100 °C in the range of 5000 kW(th) to 100 MW(th). Gas cooled reactors in the NERVA program are designed for 200 kW(th)/kg with outlet temperatures of 2000 °C in the range of 1500 MW(th). An advanced version (the rotating bed reactor or RBR) was projected to 2700 °C operation in the 1000 to 2000 MW(th) range. Liquid and gaseous fueled reactors have also been investigated but do not appear to have any significant advantages over the solid fuel reactors described above. Current technologies are summarized in Table 2.6 and constitute benchmarks for judging new technology in this area. The next section describes the basis for comparing various solar and nuclear energy systems.

2.1.5 Basis of Comparison

The only flight tested paraboloidal concentrators are those which have been developed for communication satellites. These are on the order of 2 to 10 meters in diameter and are not covered with optical quality reflecting surfaces.(37) Nevertheless, some very precise parabolic antenna have been designed and built and should be examined for contour control and pointing accuracy.

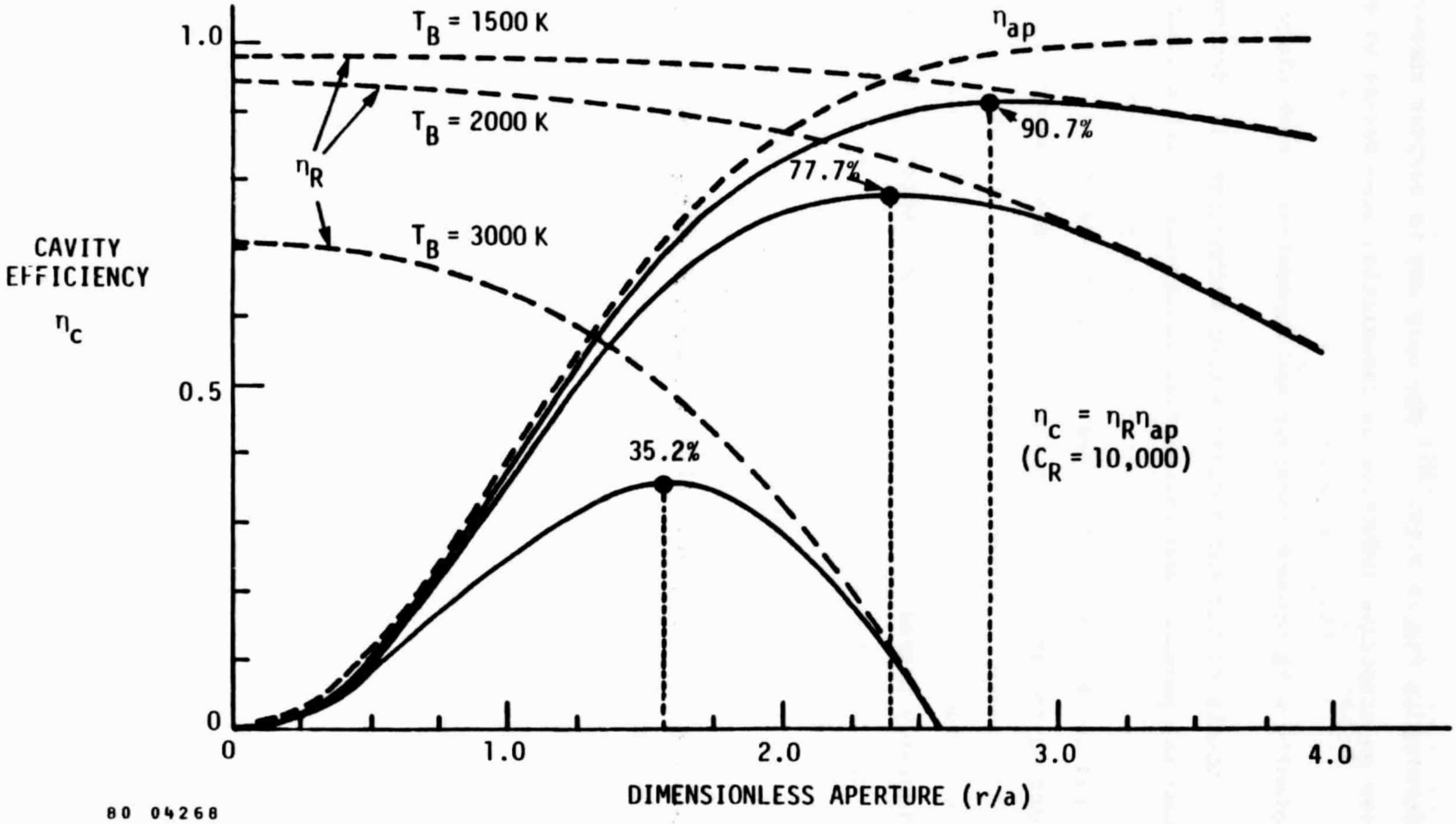

Figure 2.15. Solar Cavity Efficiency (Reference 35)

Table 2.6

Benchmark Data for Solar Collectors, Receivers and Nuclear Power Sources

Solar Collectors	
Paraboloidal (Sunflower Project)	
Size (m-diameter)	10
Reflectivity EOL (yrs)	85%
Concentration Ratio	500
Mass/Area (kg/m^2)	2
Photovoltaic Flat Array (Orbital Workshop - Complete Deployable System)	
Size (Area(m^2))	200
Mass/Area (kg/m^2)	2
Solar Cavity Receiver (Sunflower Project)	
Aperture (diameter-m)	0.5
Temperature (°K)	600
Specific Mass (kg/kW(th))	2
Nuclear Power Source	
Isotopes (Pu^{238}) [MHW Power Source]	
Power per Module (W(th))	2400
Temperature (°K)	1350
Specific Power (W(th)/kg)	115
Liquid Coolant Reactor (SNAP 10-A)	
Power per Module (kW(th))	43
Temperature (°K)	1070
Specific Power (kW(th)/kg)	20

The key features of solar concentrators are size, concentration ratio, mass per unit area, and reflectivity over a ten year lifetime. The need for higher power, higher efficiency, lighter weight power systems will require larger concentrators, higher concentration ratios, lower specific mass, and better retention of reflectivity. The size, concentration ratio, specific mass, and reflectivity for the Sunflower mirror are summarized in Table 2.6.(9) With development one might reasonably expect to be able to extend the same structural concepts to paraboloids of 30 meter diameter, but not much larger, for single concentrators. Deployment is limited to approximately 10 m diameter mirrors; larger sizes will probably have to be assembled in space.(38) These limits are imposed by the concentration ratio, since small deflections from the paraboloidal shape will seriously distort the size of the focal spot and diminish the concentration ratio. The values shown in Table 2.6 are chosen for a single device. Clearly higher concentration ratios and lower values of mass per unit area(6) have been achieved by smaller diameter concentrators. The new and advanced concentrator technology discussed below aims at significant improvements beyond the benchmarks in one or more of the categories shown in Table 2.6.

Similarly, deployable flat arrays for photovoltaics up to 25 kW BOL rating (i.e., 200 m^2) have been successfully used in space(39) as well as lightweight deployable arrays of 50 to 100 W(e)/kg.(40) This size also establishes the basis of comparison for new and advanced deployable array technology.

No solar thermal receivers have been flight tested. The Sunflower project represents the closest to a basis of comparison since it was designed as a space power system and tested on the ground. Its parameters are 0.5 meter aperture, a specific power of approximately 500 W(th)/kg, and an operating temperature of 600 $^{\circ}$K.(9)

Radioisotope sources serve as the basis of comparison for the low power range of nuclear energy sources in modules of 2400 kW(th) and 50 W(e)/kg at 1350 $^{\circ}$K.(16) At the higher powers, SNAP 10-A was flight tested at 43 kW(th) at temperatures of approximately 800 $^{\circ}$C and 20 kW(th)/kg.(16)

2.1.6 Applicability to Generic Missions

Table 2.7 shows the applicability of solar collector/concentrators, solar receivers, and nuclear energy sources to generic missions. Generally, these missions can be distinguished on the basis of absolute level of power requirements, mission duration, space environment (i.e., charged particle and solar radiation flux intensities) and energy storage requirements. In the particular case of earth orbits, nuclear energy source applications have an asterisk as a reminder that safety issues must also be resolved before certain types of nuclear sources can be used.

Clearly, nuclear sources will continue their historic role for far sun missions. In those instances where long term energy storage (i.e., batteries) might be the conventional technology, nuclear sources may play a role as an attractive alternative, especially if specific power is a strong mission determinant; for example, in novel missions such as lunar surface, and returnable missions for outer planet exploration.

Solar electric propulsion is the principal approach for deep space missions including those to comets and missions out of the ecliptic plane. Solar electric propulsion combined with local use of chemical propulsion may also be used for exploring the outer planets. Radioisotope power may also be used as an auxiliary energy source for these missions.

Solar energy collection for large photovoltaic arrays and for solar thermal power systems is indicated for specific missions in the near-earth category where solar insolation is significant and where the trade-off between thermal and photovoltaic power systems is still in debate. This trade is still quite an open question at the higher power levels (i.e., 50 kW and above).

2.1.7 Advanced Technology Assessments

New and advanced concepts are discussed here which have been suggested as ways to improve the performance of solar and nuclear energy sources compared to present technology. While the list is not complete, an attempt has been made to contact individuals and groups carrying on

Table 2.7

Applicability of Energy Sources to Space Power Missions

Mission	Comment	Applicability		
		Flat & Low Conc.	High Conc.	Nuclear
Near Earth Satellites	Cost is important, weight is moderately important, efficiency to reduce array size is important.	Yes	Yes	Maybe*
Geosynchronous Satellites	Weight and useful lifetime very important, high power increasingly important.	Yes	Yes	Maybe*
Near Sun Missions	Thermal control, including solar concentrators to shield spacecraft desirable.	Yes	No	Yes
Planetary Orbiter Missions	Missions may include inner & outer planets, nuclear sources are attractive, high power important.	Yes	Minor	Yes
Energy Conversion for Space Propulsion	Propulsion energy needs include orbital transfer, planetary & deep space exploration; high power important.	Yes	Yes	Yes
Space-to-Space Power Transmission	Concentrated sunlight and/or high specific power is important; high absolute power important.	Yes	Yes	Yes
Deep Space Mission	Radioisotope or reactor power; long life very important.	No	No	Yes
Lunar Surface	Continuous high power important.	No	No	Yes

*LEO and GEO missions subject to nuclear safeguards.

research in this area and to review their ideas. An assessment of the potential for improvement is presented in each case where sufficient data exists. In those cases where data is lacking, an estimate of likelihood of improvement is made along with suggestions as to the desirability of generating data for a more complete assessment.

2.1.7.1. Solar Collectors and Concentrators

Large Deployable Photovoltaic Arrays

While photovoltaic power systems with up to 25 kW capacity have been successfully flown, arrays larger than this have not been flight-tested, and the use of newer technologies permitting lower power-specific mass would be needed for such future, larger arrays. For much higher power levels, the need to assemble or even to fabricate arrays in space will evolve from the payload weight restriction of the available spacecraft. At the intermediate to high power levels (that is, from 50 kW to 1 MW), the relative merits of deployment versus assembly in space are not well determined. Individual studies of these alternatives are ongoing,[41] but there appears to be a need for a broad comparative study of the trade-offs between these two options, including a discussion of the size (e.g., power) at which assembly in space becomes the desirable option. The potential benefits of large deployable arrays are substantial in the 50 kW to 1 MW power range, because this is, in all likelihood, the power range for greatest growth of new missions. Further, it would appear initially that space fabrication capabilities might be unjustifiable until much larger powers are required (e.g., for SPS power systems) because of the additional mass in orbit associated with array fabrication units.

Lightweight Concentrating Collectors

A variety of very lightweight reflectors have been proposed which promises to reduce the mass per unit area by approximately a factor of 10.[42] These concepts utilize metalized plastic films (e.g., Kapton) stretched flat over a tensioned frame. A large number of small flat

surfaces can be used to approximate a paraboloidal surface, as shown in Figure 2.14, so that rather high concentration ratios can theoretically be achieved in this fashion. However, each individual frame would need to be positioned and held in position. The implications for the backing trusses suggest that something on the order of 1 mrad slope error would tolerable and practical in truss sections which are as wide as they are deep.[43] The alternative is to use an active positioning system involving feedback control, sensing devices, and some form of mechanical or electromechanical drive for positioning. Also, the lifetime of reflective surfaces is not well established for thin films; a resurfacing concept may be needed in order to make them retain a reasonable fraction (i.e., 85 percent) of the reflectivity available at the beginning of life.

Small figured reflector sections may also be achievable through controlled electrostatic distortion of thin films. This would permit high concentration ratios with fewer sections at the expense of a continuous but relatively small power drain due to, for example, charge leakage and the control functions.

Rather little is known about the support structure required for large concentrators. Another NASA program is funding R & D in this area.[44] It would be worthwhile tracking work in that program (e.g., associated with large communication satellite antennae) which must satisfy very similar constraints to those of the solar concentrator.

Large scale solar concentrators would enable an entirely new class of large thermal power systems having high temperature receivers and, hence, the ability to reject waste heat with small area radiation and to convert sunlight to useful work efficiently. For this reason we recommend initial studies of large, lightweight concentrators. This project area should consider novel concentrator technologies (i.e., thin films, reflective concentration ratios). The goals for such systems should be less than 200 g/m^2 (i.e., 10 times lighter than the benchmark), reflectivity (averaged over lifetime) of 85 percent or better, and concentration ratios of 5000 or more for concentrators 10 meters in diameter or larger. Thin, metallized films of 4 g/m^2 have been proposed

for solar sail systems planned for the mid-1980s. This approach with a suitable support structure may prove fruitful and, ultimately, might lead to solar concentrators on the order of 10 g/m^2.[43]

2.1.7.2 Thermal Receivers

Many of the advances in solar receiver technology now being tested for terrestrial applications need to be explored for use in space. These include ceramic tube heat exchanger receivers capable of sustaining high temperature operation, secondary reconcentrators to improve the concentration ratio at the receiver, and windowed receivers with ceramic honeycomb direct absorbers through which the working gas circulates. Each of these concepts aims at higher temperature, higher thermal efficiency operation. Their use in space would relax some of the materials requirements posed by exposure to air for an Earth-based system. Conversely, pressure and stress requirements may be somewhat more demanding in the vacuum environment of space.

A variety of novel solar thermal receivers have also been proposed which have the potential for increasing the receiver operating temperature while maintaining a relatively low reradiation temperature. One of these concepts emphasizes the use of high pressure alkali metal vapors where direct solar absorption occurs in a compound molecular state (i.e., dimer) of the gas.[45] Another concept uses a working gas doped with another absorbing molecule (i.e., CN) and a third uses fine particulates (e.g., carbon) suspended in the gas to absorb the sunlight.[46,47] Each of these relies on the fact that concentrated sunlight can be absorbed directly within the working fluid without first having to heat, and transfer heat through, a solid surface (e.g., tube walls in a cavity solar receiver). Therefore, the working fluid temperatures can exceed the limits normally imposed by heat exchanger technology. If the working fluid is optically thick, then it will support a thermal gradient by injecting cooler gas near the front of the cavity where the radiation enters so that it flows towards the rear of the cavity as it heats up. The reradiation losses are, therefore, characterized by the cooler temperatures near the front of the

cavity. This technique allows the overall cavity efficiency to be high despite the high exit temperatures of the gas. The cavity walls can be transpiration cooled by injecting some of the gas through the wall into the cavity.

The critical technologies in these concepts have each been explored to some degree. Specifically, high temperature windows for solar receivers are just beginning to receive attention in DOE's Advanced Solar Thermal program. The longevity of high temperature working fluids in the state of purity, particulate suspension, or absorber doping, etc. required to keep their absorptivity high is not well understood. The design of the absorption cavity, etc., is also an open question which needs to be answered. The receiver may be able to handle heat fluxes to the limit achievable with concentrating mirrors [e.g., 10,000 suns or 10 MW((th)/m^2] as the technology of cooled windows advances.

An illustrative concept, the Rotating Bed Solar Absorber (RBSA), is shown schematically in Figure 2.16. Solar energy is focused onto the inner surface of a rotating fluidized bed where it is absorbed by the inner layers of suspended particles. Rapid mixing in the fluidized bed transfers the absorbed energy to the other particles, resulting in a temperature gradient in the bed. The fluidizing gas enters through the rotating porous cylinder or "crib" that holds the fluidized bed. The crib is kept at the gas inlet temperature with the gas temperature increasing as it moves through the bed until it exits from the inner fluidized surface. Performance parameters for the RBSA are indicated in Figure 2.16. This is just one of several concepts being proposed.

Development of high temperature solar receivers for space power systems will involve one or more of the following areas:

- Mirrored collectors/concentrators

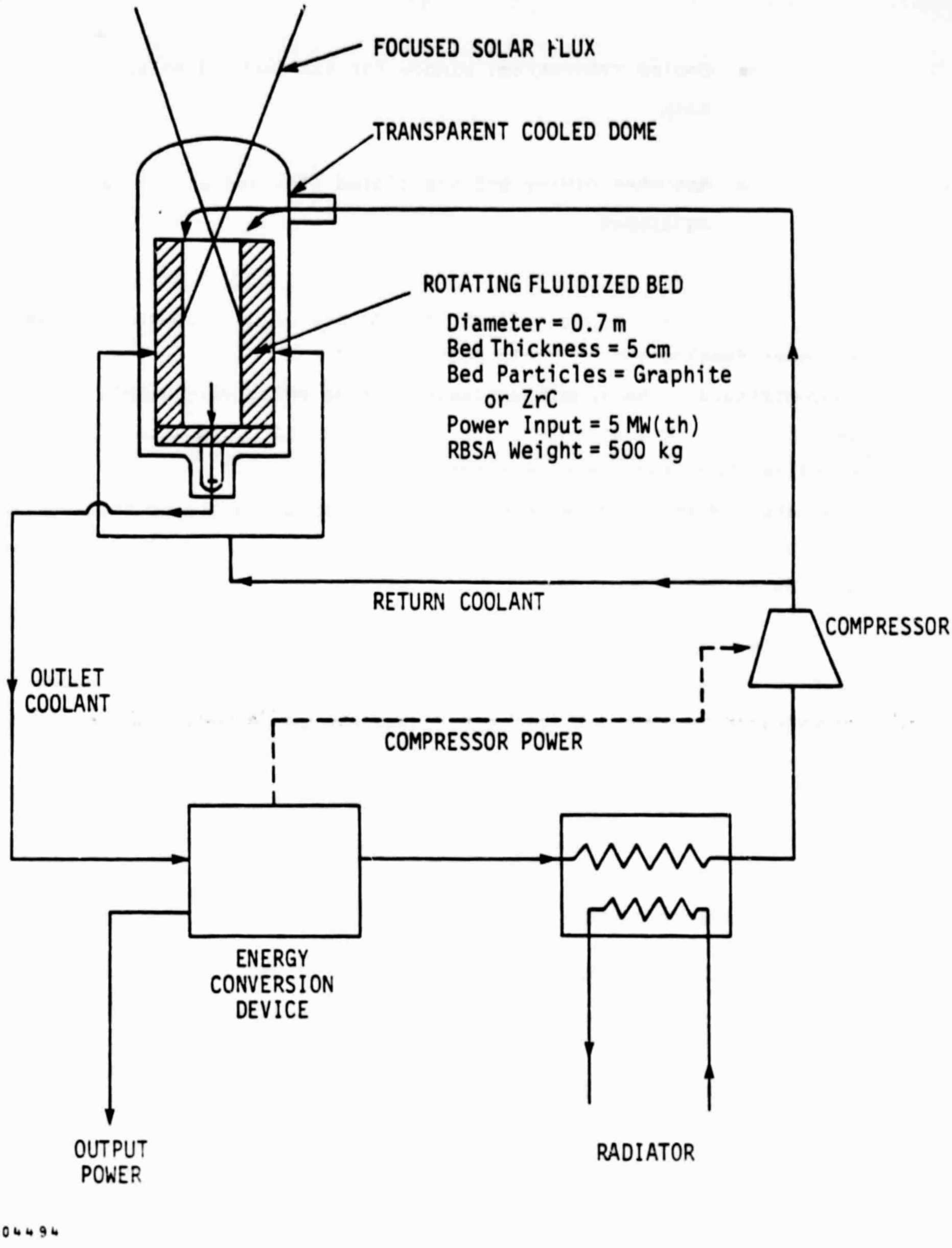

Figure 2.16. Rotating Bed Solar Absorber (RBSA) for Space Power.

- Cooled transparent window for the focused solar flux

- Absorber cavity and associated flow and mechanical equipment

The above ranking reflects the degree of development required, with the most development probably being needed for the mirrors and concentrators. The absorbing cavity can be relatively simple mechanically. For example, work on the thermal hydraulics of rotating fluidized beds indicates that heat transfer and bed stability should be adequate. Work would be needed on long term integrity of the receiver materials. Design studies of the solar absorption in the receiver would also be needed.

Development of the windowed receivers appears to be feasible. Windows would require active cooling to remove absorbed and convectively transferred energy, but the heat fluxes should be quite low (a few watts/cm^2) and could be readily handled. Stress distributions (both primary and thermal) and mechanical design (particularly scaling) would also have to be investigated.

2.1.7.3 Radioisotopes

Very little remains for improvement of radioisotopes as an energy source. These are well established as a long-lived source for outer planetary exploration. Most of the continuing development in this area will focus on making small but useful adjustments in design to make the sources more resistant to atmospheric ablation and impact break-up for use in Earth orbit applications. We recommend that the isotope heat sources not be the specific subject of the Advanced Energetics Program.

2.1.7.4 Nuclear Reactors

Advanced reactors deserve serious attention as high power, low specific mass heat sources. NASA needs to adopt a position on what reactor sources, if any, it will need in the years to come. The earlier such a position is reached, the sooner the necessary R & D can begin on the long lead items needed for a successful reactor program. The SPAR program at LASL represents just one of several alternate reactor concepts that can be pursued. While it has the simplest coolant system (i.e., heat pipes), it is by no means necessarily the most desirable in terms of absolute power level or specific mass. As discussed earlier in this section, a range of reactor concepts exists with varying degrees of complexity and level of development to provide power to nearly any mission conceivable. Reactors do not need on-board energy storage, are long-lived, and can be made to operate very reliably, offering a very attractive energy source for NASA. While the Advanced Energetics Program need not specifically concern itself with the whole of a reactor concept, it can help to decide which reactors are most desirable within the context of various mission classes and help NASA arrive at an appropriate R & D posture on space reactors. Individual novel reactor concepts may also arise from such a study, which need a proof test and/or further analysis before their promise is clear. Such concepts would be worthy of attention in the Advanced Energetics Program once the basic direction of NASA's commitment in the nuclear reactor area has been established.

2.1.8 Energy Sources Conclusion

This section has emphasized solar energy collection for photovoltaic cells, solar thermal power systems, and nuclear energy sources. The greatest advances appear possible in those areas leading to larger power systems. Large solar arrays and large, lightweight solar concentrators are enabling technologies in this respect, as are the development of high temperature solar thermal receivers. One of the chief benefits of developing higher temperature solar receivers is to operate more efficient power cycles and to reject waste heat at higher temperatures in order to

reduce the overall power system weight. The use of large nuclear power systems in space appears technically feasible considering the enormous amount of R & D already performed in that area. The most important question concerns a need for a definite NASA posture on the use of nuclear power in space.

As a result of assessing the current status of energy sources for space power and suggestions for new and advanced technology in this area, we recommend the following areas of research:

1. LARGE DEPLOYABLE ARRAYS: Novel concepts for handling arrays greater than 50 to 100 kw should be investigated at a modest level and tested in the laboratory at full scale to prove the technical concepts and establish problem areas needing engineering development. Increasing the size of the deployable arrays would help to guarantee the continued success of the photovoltaic cell as a mainline space power source into the future, as NASA's power requirements grow.

2. LIGHTWEIGHT SOLAR CONCENTRATORS: New and advanced structural concepts and reflecting materials (e.g., thin metalized films) need to be studied (1) to determine the best way to assemble a large, high concentration ratio concentrator in space, and (2) to test specific reflector concepts for durability, rigidity, controllability, and end-of-life reflectivity. Lightweight solar concentrators represent a technological advancement which should enable the use of high power, compact solar power systems.

3. **SOLAR THERMAL RECEIVERS:** Several high temperature, lightweight solar receiver concepts have been suggested which have the potential for allowing higher thermal cycle efficiencies and/or rejecting waste heat at relatively high temperatures to reduce radiator weights. The ability to use high temperature working fluids already exceeds the ability to produce high temperatures efficiently in solar receivers. Hence, this is a key technology, enabling efficient solar thermal power systems of low power-specific mass.

4. **NUCLEAR REACTORS:** A position paper needs to be developed laying out NASA's requirements, if any, for high power nuclear reactors for space power. This paper should also review the need for advanced research in those areas corresponding to NASA's reactor requirements.

2.2 Energy Conversion

2.2.1 Introduction

This section reviews the state-of-the-art of energy conversion technologies including photovoltaic cells, thermoelectric converters, thermionic converters, thermal dynamic cycles, and a variety of other energy conversion concepts. The technology for capturing or releasing energy from an energy source has already been discussed in Section 2.1, and converters that transform stored energy to electricity are included in the following section (2.3) on energy storage (e.g., batteries, fuel cells, fly wheels, etc.). Table 2.8 shows a list of some of the principal technologies considered in this section. Wherever overlap occurs with Sections 2.1 and 2.3, the corresponding technologies are referred to for the reader's assistance.

Table 2.8

Principal Energy Conversion Technologies

DIRECT CONVERSION
Photovoltaic Cells
Thermoelectric Converters
Thermionic Converters
DYNAMIC CONVERSION
Gas Turbines
Free Piston Expander
Energy Exchanger
MHD Generators
NOVEL ENERGY CONVERSION CONCEPTS
Photo-assisted Electrolysis
Photo Diodes
Thermo Photovoltaic Conversion
Thermo-Electrochemical Conversion

Energy conversion technologies for space power systems are in varying stages of maturity, development, or conceptualization. The latter category includes photovoltaic cells and thermoelectric converters. Clearly, photovoltaic cells have been preferred because of their reliability and elegant simplicity. Radioisotope powered thermoelectric converters have similar attributes and have been used for missions far from the sun where solar radiation is too faint for practical collection, for missions where fixed orientation to the sun is undesirable, or for missions needing power during a long period of occultation (i.e., planetary surface exploration). Solar thermoelectric converters have also been investigated for use near the sun. Thermal dynamic systems such as Brayton cycle gas turbine and Rankine cycle turbine power systems have been extensively developed for space power systems but are not used for present spacecraft. The remaining technologies have only been considered, or in some cases developed to a lesser degree, for actual application.

The relative quality of the available data is of importance for any comparative assessment. Because of the large differences in the development status of the various power systems considered, the quality of the data, by necessity, varies considerably. The best data available is that stemming from in-orbit experience. However, it requires that the power system has remained in an operational status for some time. This is not the case for most of the advanced power systems, some of which are in a conceptual stage, with only projections to in-orbit performance being possible.

Special DOD requirements may exist for specific attributes of a power system which may have greater weight than the attributes of interest for normal NASA service. Such special attributes will not be considered in this assessment.

The assessment of current technology follows a fairly uniform set of criteria for comparing disparate concepts. These are generalized as the power-specific mass, the system life, and the price of power. In many cases, these criteria are mission dependent, since both the mass and the power deliverable at the end of the system's design life depend on the

mission orbit, mission lifetime, and payload requirement. Thus, a second set of criteria more specific to each particular converter technology is used to develop a preliminary ranking before trying to express the merits of a given type of converter more generally. In addition, while efficiency is not a good direct measure of converter merit (generally, specific power is the most important criteria), component efficiency does have a strong system-wide effect in terms of total system weight (e.g., influencing both collector and radiator size in a solar thermal power conversion system). Therefore, we include it in the technology evaluations which follow.

Materials play an important role in the development of higher performance systems. In some cases, especially in established conversion technologies, an evolutionary materials development process has been underway for many years. For example, high temperature materials for turbine blades permit higher cycle temperatures and higher cycle efficiency. Similarly, photovoltaic cell materials have been improved by using higher purity silicon and better dopant diffusion processes. However, the development of materials already in use today is unlikely to lead to major, non-incremental improvements in converter performance. The most likely paths to such improvements are the use of different or new materials and the conceptualization of new converter types or configurations. Such advanced systems will face a relatively well established set of benchmarks to compete against, as discussed in Section 2.2.5. A variety of these new and advanced ideas are assessed in Section 2.2.7 summarizing the status and potential of each.

The main conclusions of this section are that significant improvements in performance are available in both photovoltaic and thermally driven converters. A multitude of advanced converter concepts have been suggested of which only a select group have shown a realistic potential for non-incremental improvement over the performance benchmarks. In the area of photovoltaics, these potential improvements are associated with better methods of encapsulating cells, providing increased radiation resistance and higher single cell efficiency. Both multi-bandgap cells and high solar concentration cells have been singled out for attention. These

technologies are being developed within NASA already; specific areas not presently covered in these programs are called out for support. Thermal energy converters promising large improvements uniformly require high temperature sources and radiators as part of the power system requirements to achieve these improvements (see Section 2.1 for high temperature sources and Section 2.4 for high temperature, lightweight radiators).

In other respects, the advanced thermal converter category recommended for support is very diverse, ranging from new thermoelectric materials and electrode configurations to high temperature expanders for thermal dynamic systems. Thermal cycle efficiencies in excess of 40 percent appear feasible for several of the systems employing these converters with associated reduction in power-specific mass. The thrust to higher powers is the driving force behind the reconsideration of thermal energy conversion systems. A number of systems studies to investigate the needs and trade-offs of thermal energy vs. photovoltaic conversion systems is recommended, which should account in detail for new ideas in each of these areas.

2.2.2 Conversion Requirements

Energy conversion requirements from 20 kW up to megawatts of power have been identified in planning for future missions. The requirements of man in space lead to power in units of approximately 5 to 10 kW of power per person for extended missions (i.e., where regeneration of oxygen and moisture is required). Future missions involving space platforms or large communications satellites may push power requirements up to several hundred kilowatts; power needs for orbital transfer propulsion may range upwards of 1 MW. As power requirements increase, the efficiency of conversion becomes increasingly important since the amount of rejected heat in low efficiency systems leads to very large radiator areas and, in solar powered systems, the collector also becomes a very large structure. In the case of photovoltaics, both surfaces of the collector radiate waste heat; nevertheless, the low efficiency, in absolute terms, of photovoltaic conversion still leads to very large and cumbersome arrays. Thermal power

systems may have some advantages in terms of overall system efficiency, especially at higher powers, so long as the power-specific mass can be kept small. Because of the trend to higher powers, therefore, there is a natural motivation to examine higher power, thermal energy conversion systems that scale favorably with increasing power.

2.2.3 Conversion Methods

2.2.3.1 Photovoltaic Energy Converters

INTRODUCTION

A comparative assessment of space power systems should, ideally, be based on three generalized criteria: the power-specific mass (g/W), the price of power ($/W), and the system life (Table 2.9). The determination of the power-specific mass should include the mass of the entire power system, including storage and power conditioning where applicable, and should be based on the power actually deliverable to the load at the end of life (EOL) under the actual operating conditions. The price of power should be based on the cost of the complete system, installed on the spacecraft and fully operational, and on the EOL power deliverable to the load. For some systems whose mission is power delivery, such as the SPS, the costs of launch, transfer to orbit, and assembly in orbit should also be included in the power system price. These criteria are, however, not as general as would appear initially, since both the mass and the power deliverable at EOL depend on the orbit and on the mission. The dependence on the orbit stems primarily from different radiation environments and operating temperatures attained, while the dependence on the mission stems primarily from varying requirements for energy storage and power conditioning. The system life represents the time to the appropriately defined end of the useful life of the power system. In some cases the useful life of the spacecraft system may be shorter than that of the power system.

While these generalized criteria would make the comparative assessment of different power systems rather easy and transparent, they are usually not available. Instead, a number of specific criteria are often

Table 2.9

Generalized Criteria

1. Power-Specific Mass (g/W)

   Should be for complete power system; power EOL, at in-orbit operating conditions. (Depends on orbit, mission, because of battery and PC subsystem mass, radiation environment, operating temperature.)

2. Price of Power ($/W)

   Price of complete system; power output EOL, at in-orbit operating conditions, including launch costs, where applicable. (Dependencies as in PSM.)

3. Life

   Time to appropriately defined EOL.

given (Table 2.10). The specific criteria are used, at least in part, because the generalized criteria are dependent on orbit and mission. They are, however, more specific to the particular power system and, thus, do not readily permit a comparative assessment of different power systems. The specific criteria include, for example, the power-specific mass and the price of power of a photovoltaic array alone, generally at the beginning of life (BOL), or the BOL efficiency of the photovoltaic array, or even the BOL efficiency of the solar cells themselves. Instead of the system life, degradation characteristics of specific components or subsystems are usually given. These degradation characteristics are usually given with respect to certain influences which can be readily simulated in the laboratory rather than those resulting from the combined effect of several simultaneous influences experienced in orbit. Thus, the degradation characteristics are usually given for solar cells under irradiation by 1 MeV electrons, with approximate equivalency factors for other electron energies or even protons available. Some types of solar cells have also been found to degrade under the influence of short wavelength photons. The European produced solar cells, which are prepared from float-zone refined silicon, particularly show such sensitivity. (The American produced solar cells are prepared from Czochralski-grown silicon.)

1980 TECHNOLOGY BASE OF PHOTOVOLTAIC SPACE POWER ARRAYS

Photovoltaic solar energy conversion systems have formed the vast majority of the power systems for spacecraft with mission durations greater than one to three weeks. Relatively few spacecraft have been equipped with radioisotope thermoelectric generators (RTGs), particularly those with missions far from the sun where the solar irradiance is too low to make its utilization practical. Photovoltaic arrays with BOL ratings as high as 25 kW (Orbital Workshop together with Apollo telescope mount) have been installed on spacecraft, and an upper limit for the size of photovoltaic arrays on spacecraft is no longer considered. In fact, designs of photovoltaic arrays with rating above 20 GW are actively pursued for the SPS system. A guaranteed photovoltaic system life of seven years in

Table 2.10

Specific Criteria

1. Power-specific Mass of Array, BOL

2. Price of Power of Array, BOL

3. Efficiency of Array, BOL

4. Efficiency of Solar Cells

5. Array Operating Temperature

6. Degradation Characteristics

   a. Electrons (1 MeV)
   b. Protons
   c. T cycling
   d. Pre-launch Environment
   e. Photons, if applicable

7. Quality of Available Data

   (In-orbit experience, accuracy of in-orbit performance predictions)

8. Special DoD Requirements

geostationary orbit (GEO) is now standard,[48] with ten years actual useful life a not uncommon experience.[48,49] The life-limiting item is frequently the battery rather than the photovoltaic array. In low earth orbits (LEO), with their more severe radiation environment, the useful life is usually guaranteed for one tenth of a year to five years, depending on the orbit.[48]

The photovoltaic space power systems have all been based on the use of silicon solar cells. For space application these cells are all of the "n on p" type because of greater radiation resistance, with most of nominally 10 Ohm cm base resistivity. The remainder uses 3 Ohm cm base resistivity with advantage. Modern space solar cells of high efficiency have either a texture-etched front surface with a single layer anti-reflection coating, or a multi-layer anti-reflection coating on a polished surface. The cells have a so-called back surface field (BSF) base structure, with some having an additional photon reflecting back surface (BSR).[50] The front layer, generally phosphorus diffused, is nominally 0.1 to 0.3 μm thick. The overall cell thickness is 200 to 300 μm. However, cells of only 50 μm thickness have recently been successfully fabricated with only a relatively small efficiency tradeoff (14% AMO).[51,52] Cells of 200-300 μm thickness with 14.5 to 15.5% Air Mass 0 efficiency under standardized test conditions are routinely available from current production lines.[49,53-55] Since many power system designs, to which arrays are now being delivered, are older and specify solar cells of lower efficiency, the average efficiency of the solar cells currently produced is closer to 14%, and the average array efficiency is near 13%.[53,56] A major reason for this low average cell efficiency is that substantial numbers of older cell types are still being bought. The radiation degradation of present production solar cells, measured with 1 MeV electrons at a fluence 3×10^{14} cm^2, is approximately 0.75 of the initial power output.[49]

The annual production rate of space-qualified solar cells in the United States fluctuates around 100 kW, and has not been in a growth mode in the last ten years.[53,54] The rated power of the spacecraft arrays produced is a fraction of this 100 kW number, and that of the spacecraft

launched by NASA and DOD combined seems to be less than 30 kW per year.[56] The total experience base of photovoltaic power systems in space seems to be in the range of 600 to 1,500 kW · year. This number is based on the total rated power of the spacecraft launched, multiplied by their useful life.

The systems which have been flown to date do not use optical concentration but are composed of extended flat arrays or body mounted arrays of silicon solar cells. The power-specific mass of the more recently designed arrays falls into the range of 15 to 60 g/W BOL, depending on the individual spacecraft design, and excluding the heavier body-mounted arrays.[48,49] The power-specific price for the complete array, including attachment and deployment mechanism, falls into the range of 400 to 1,000 $/W.[48,53,56] The actual power-specific price of the array for an individual spacecraft depends considerably on the size of the power system and on the type of deployment used. A considerable fraction of the spacecraft arrays delivered seem to fall into the lower part of the given price range (Table 2.11).

Two other parts of the photovoltaic power system need mentioning. They are the power conditioning system and the energy storage. The power conditioning systems used range from rather unsophisticated, low efficiency series or shunt regulators to maximum power point tracking systems with efficiencies as high as 99%. Mass, volume, price, and reliability of these systems seem acceptable. Energy storage has been found to present a bigger problem, both with respect to mass and to reliability. So far, nickel-cadmium batteries exclusively have been used for energy storage. However, Comsat has been developing nickel-hydrogen cells, with a successful flight experiment already carried out.[49]

2.2.3.2 Thermal Conversion

Thermoelectric thermal converters have been in use on spacecraft. Thermal Brayton power units and alkali-metal vapor, mercury, and organic Rankine cycle power systems have each undergone substantial development for space power systems. In addition, a variety of advanced and new thermal

Table 2.11

Technology Basis 1980: Photovoltaic Arrays

Item Assessed		Units	Current Production Si Flat Arrays
Power-Specific Mass		g/W	15-60 BOL
Power-Specific Price		$/W	400-1000
Life	GEO	y	7-10
	LEO	y	0.1-5
Production Rate		kW/y	~100
Experience Base (total flown)		kWe	600-1500
Array Efficiency		%	13 ave.
Solar Cell Efficiency		%	14.5 ave.
Radiation Degradation @ $3 \cdot 10^{14} cm^2$ (1 MeV)		-	~0.75

power conversion concepts have been proposed which have some potential for increasing power system performance over what can be achieved at present. Each of the relatively well developed thermal energy conversion approaches is described below, summarizing the current status and expected performance of these technologies and the possible impediments to their development. The advanced technologies are assessed in Section 2.2.7.

THERMOELECTRIC CONVERTERS (TE)

Thermoelectric technology has been developed as a reliable power source which will provide watts to hundreds of watts of electric power using available isotope heat sources. There have been two types of applications for these devices: 1) remote site or undersea where air or water cooling is available, and 2) space applications where rejection temperatures are required to be higher to reduce system weights.

The majority of research has been directed toward achieving reliability with only limited effort toward new materials or higher temperature materials. It is only recently, since the proposed development of a high temperature reactor, that higher temperature thermoelectric materials are being considered.[57,58]

Typical hot junction temperatures for $(Bi,Sb)_2(Te,Se)_3$ system are in the 200 to 300 ^{o}C range (475 to 575 ^{o}K). Degradation rates increase as a function of hot junction temperature from diffusion mechanisms, vaporization mechanisms, Kirkendall void formation, etc. Figure 2.17[59] is a degradation curve for the $(Bi,Sb)_2(Te,Se)_3$ system; similar behavior can be expected for other thermoelectric systems. The low operating temperature for this system makes it of little interest for future space power, although RTGs of this type were used in the 1960s.

The system which is being used now for space power is the Si-Ge thermoelectric generator. This generator has flown on LES 8 and 9 missions, Voyager 1 and 2, and is planned for Galileo and the International Solar Polar Mission. Figure 2.18[60] shows the overall system efficiency is approximately 6% (net electrical output/total thermal input) BOL; the

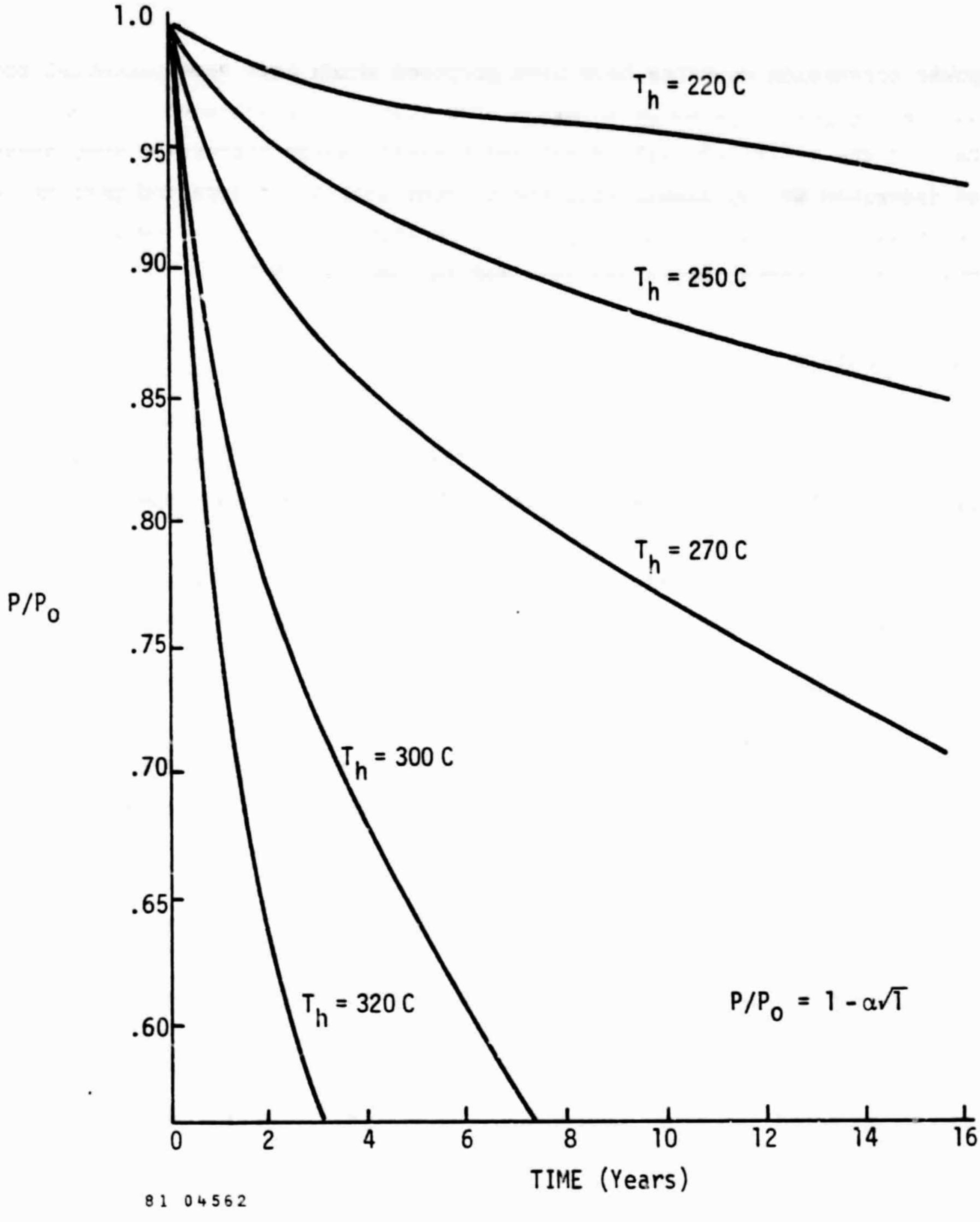

Figure 2.17. Degradation Rates of $(Bi,Sb)_2(Te,Se)_3$ Thermoelectrics as a Function of Hot Junction Temperature. (Reference 59)

corresponding EOL efficiency is 5.5%. This figure can be regarded as typical of current technology. Improvements in overall system design allow increased mission length and lower specific mass for the system (Figures 2.19 and 2.20).

THERMIONIC ENERGY CONVERTERS (TEC)

TEC research and development has been concentrated on individual converters and small clusters of converters; relatively little data exists on entire systems tested for long periods of time. As a consequence, assessing the performance for a TEC system is difficult. The operating temperature for TEC (1400 $^{\circ}$K and above) makes electron bombardment heating the most practical approach for laboratory devices. Most research devices are planar in design and have, as a consequence, large extraneous heat losses which make high-confidence calculations of efficiency difficult. However, cylindrical devices have been tested which have smaller extraneous heat losses, resulting in increased confidence in the observed efficiencies. Even in this case the effectiveness of coupling between individual TEC devices, as well as coupling between the TEC system and the heat source, can only be estimated and should not be viewed in the same perspective as the performance data from other prototypical systems.

While substantial efforts have been made in the United States and abroad to develop in-core thermionic reactor fuel elements for nuclear reactors[61] with engineering prototypes tested for tens of thousands of hours and more, these have generally been designed for thermal reactors. Significant problems of device distortion and failure due to fuel swelling are encountered when the equivalent technology is used in compact fast reactors suitable for space. The resolution of these lifetime problems will lead to a significant advance in TEC space applications.[62] Out-of-core thermionic converters are currently being investigated in conjunction with the SPAR space nuclear reactor program. In this context, the thermionic diodes are integrated into the high temperature end of heat pipes which carry waste heat to the radiator.[63]

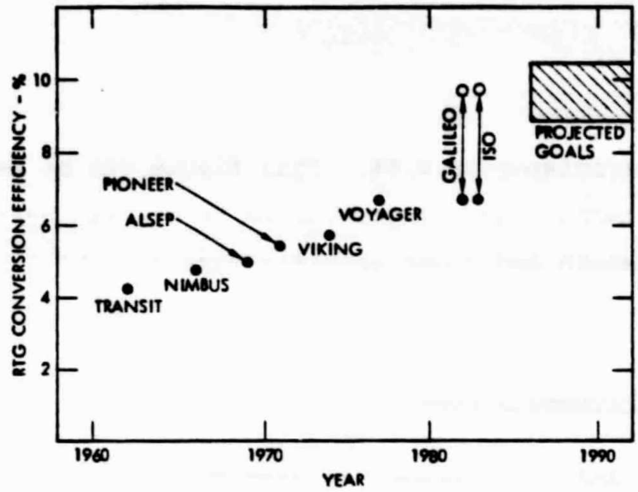

Figure 2.18. RTG Conversion Efficiency (Reference 60)

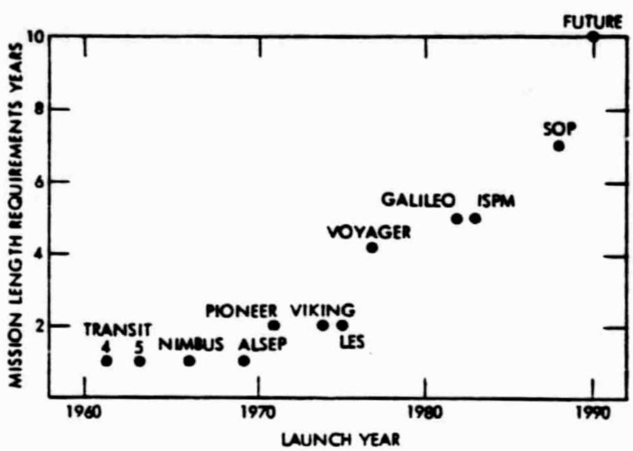

Figure 2.19. RTG Mission Requirements (Reference 60)

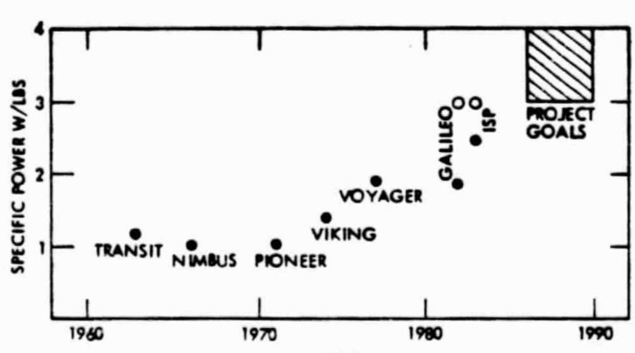

Figure 2.20. RTG Specific Power (Reference 60)

TEC are complex devices in that performance is affected by device size (e.g., massive electrodes have small I^2R losses but may be prohibitively heavy), electrode spacing, cesium vapor pressure in the interelectrode area, as well as the high and low operating temperatures of the devices.

Results of various TEC tests are commonly presented as electrode voltage vs. current density (A/cm^2 of emitter area) as a function of the above variables which affect performance.[64] These curves are compared with the theoretical output, a Boltzmann line intersecting the saturation level at the contact potential. Typical curves are shown in Figure 2.21. Approximate efficiencies can be inferred from these curves. Electrode efficiencies for converters typical of today's technology are in the range of 12%. With an 'optimum' lead the device efficiency would be in the 10% range, and incorporation of such converters into a realistic system design would result in further losses, reducing efficiency to the 8% range. A converter with these efficiencies using current materials technology would have an emitter temperature in the 1600 ^{o}K range, a collector temperature in the 750 ^{o}K range, a power density of 3 to 5 w/cm^2, with an output voltage approximately 0.5 to 0.7 volts. These numbers must be viewed as approximate since maximization of efficiency requires a converter designed for the specific point of operation, and maximum efficiency does not occur at the same operating point as does maximum power output.

Performance and efficiency improve rapidly with increased emitter temperatures. Emitter temperatures of 1800 ^{o}K have produced electrode efficiencies in the 16% range.[65] Similarly, emitter temperature reductions below 1600 ^{o}K quickly result in drastically reduced power output.

TEC has two unique, desirable features for power conversion systems applications:

(1) Demonstrated long life, 46,000+ hours of operation without significant degradation in performance, and

(2) High heat rejection temperatures which minimize radiator weights for space systems.

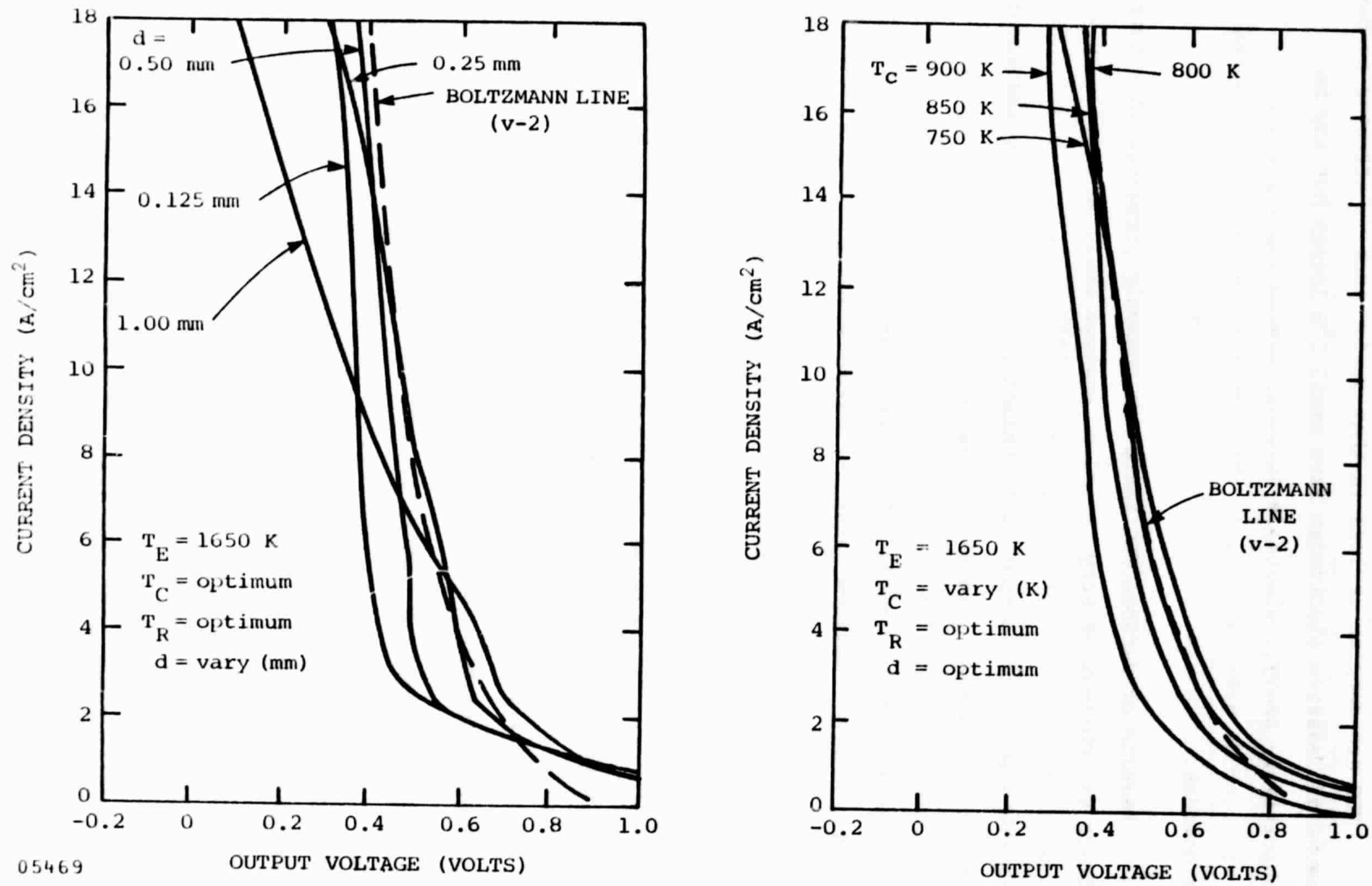

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Figure 2.21. Thermionic Converter Output with Varying Collector Temperatures and Electrode Spacings using a molybdenum emitter and molybdenum oxide collector. (Reference 64)

A substantial gap appears between the predictions of high efficiency by researchers in this field (e.g., 26% theoretical optimized lead efficiency vs. the 10 to 13% experimental values) and the results of experiments. Clearly, a potential for improved performance exists, but researchers have made slow progress towards these goals. Ways to enhance TEC performance are suggested in Section 2.2.7.

BRAYTON CYCLE TURBINES

A variety of gas turbine space power systems have been designed and tested over the past twenty years to help identify the potential performance for these systems. A typical Brayton power system is shown in Figure 2.22.[66] The system includes the solar collector, receiver, heat source heat exchanger, turbine, compressor, recuperator, generator, and waste heat radiators. Evidently, an economy of scale is available for power-specific mass, as shown in Figure 2.23.[67] The upper limit on module size is generally determined both by the mission as well as by the power units themselves, according to an optimizing criterion such as minimum weight in orbit or minimum cost for the mission. There is good reason to suggest that the economy of scale reaches a lower limit in the vicinity of 4 kg/kW_e and does not continue much further downward along the dashed line graphed in Figure 2.23.

Actual gas turbine power systems have been tested for use in space only at the lower end of the power scale shown in Figure 2.23; that is, from 2 to 15 kW(e).[68,69] At 15 kW(e), a complete Brayton power generation system operated at 1600 ^{o}F with power plant efficiencies of 29% (excluding concentrator and receiver losses). Long run duration tests of 38,000 hours were carried out on this system with exceedingly high reliability. Materials tested included TZM for the turbine rotors (64,000 hours at 1600 to 2000 ^{o}F) and ASTAR-811C (250,000 test hours at 1600 to 3000 ^{o}F) suitable for the turbine casings, ducts, and heat exchangers.[70,71] Examples of similar rotating units are shown in Figure 2.24. Incorporation of separately tested, improved components is expected to raise the power plant efficiency to 32%.[68]

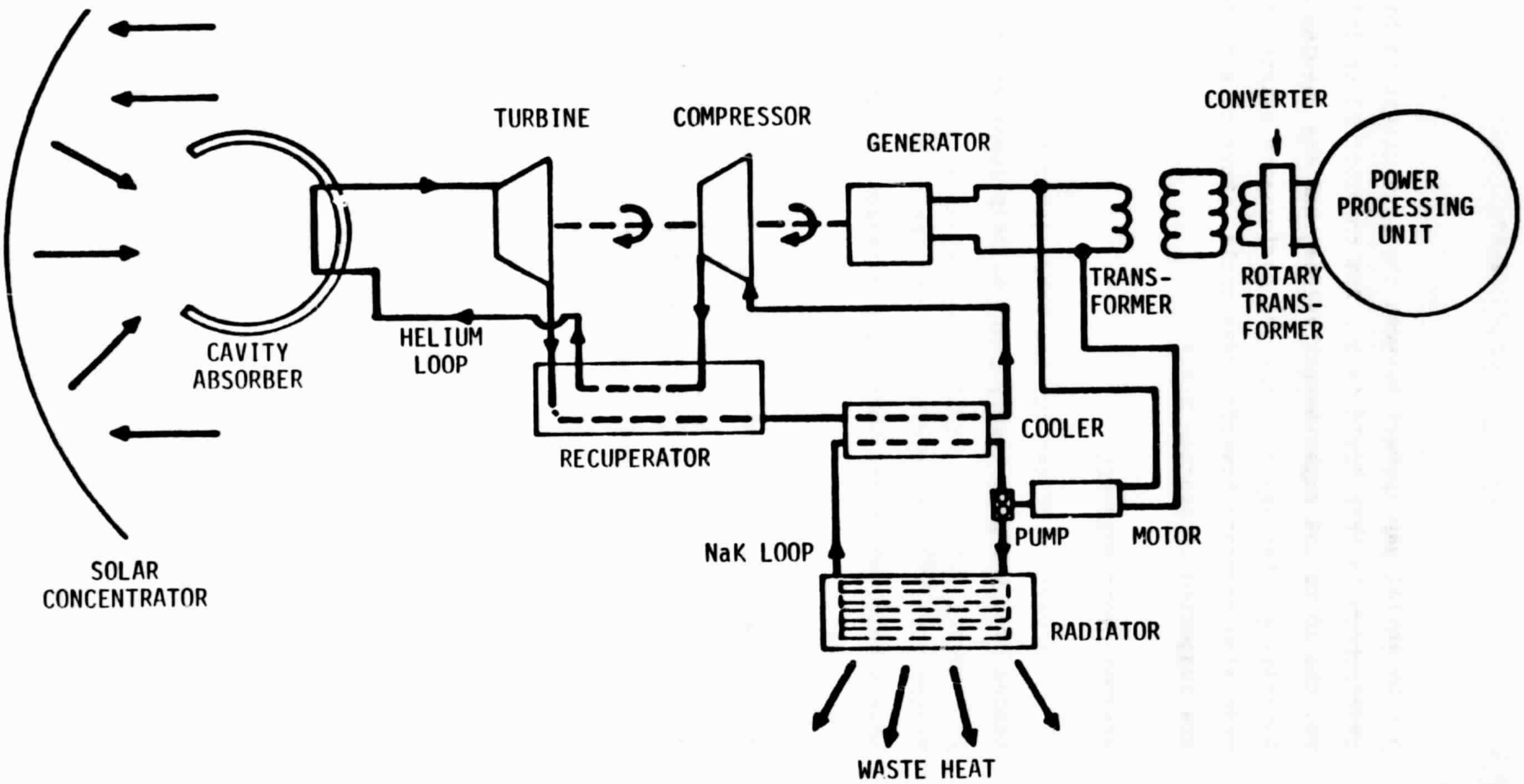

Figure 2.22. Example of a Solar Brayton Power System (Reference 66).

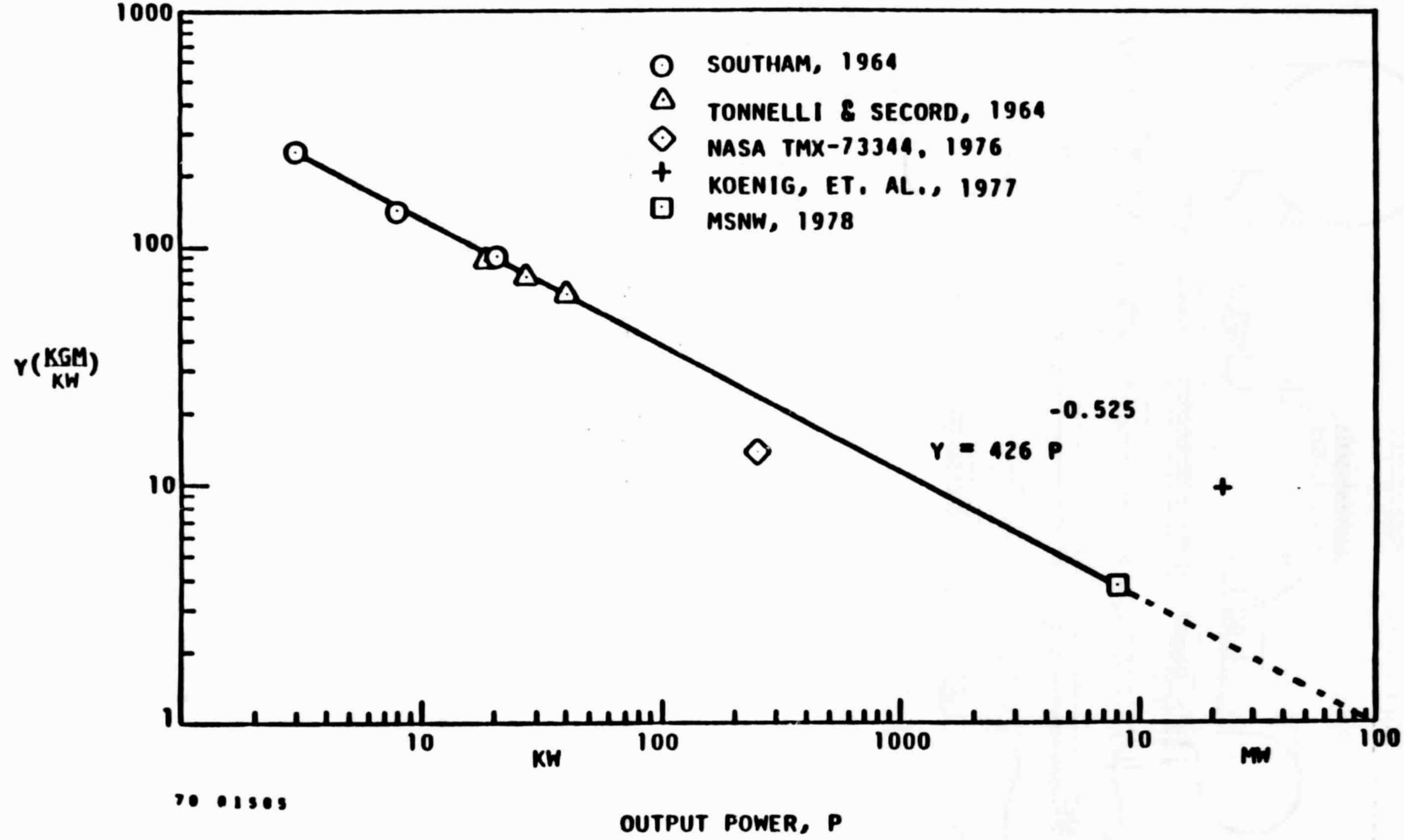

Figure 2.23. Solar Brayton Systems, including weights of collector, power units, and radiators. Solid line indicates approximate curve fit to design points: dashed line indicates uncertain extrapolation from large scale designs. (Reference 67)

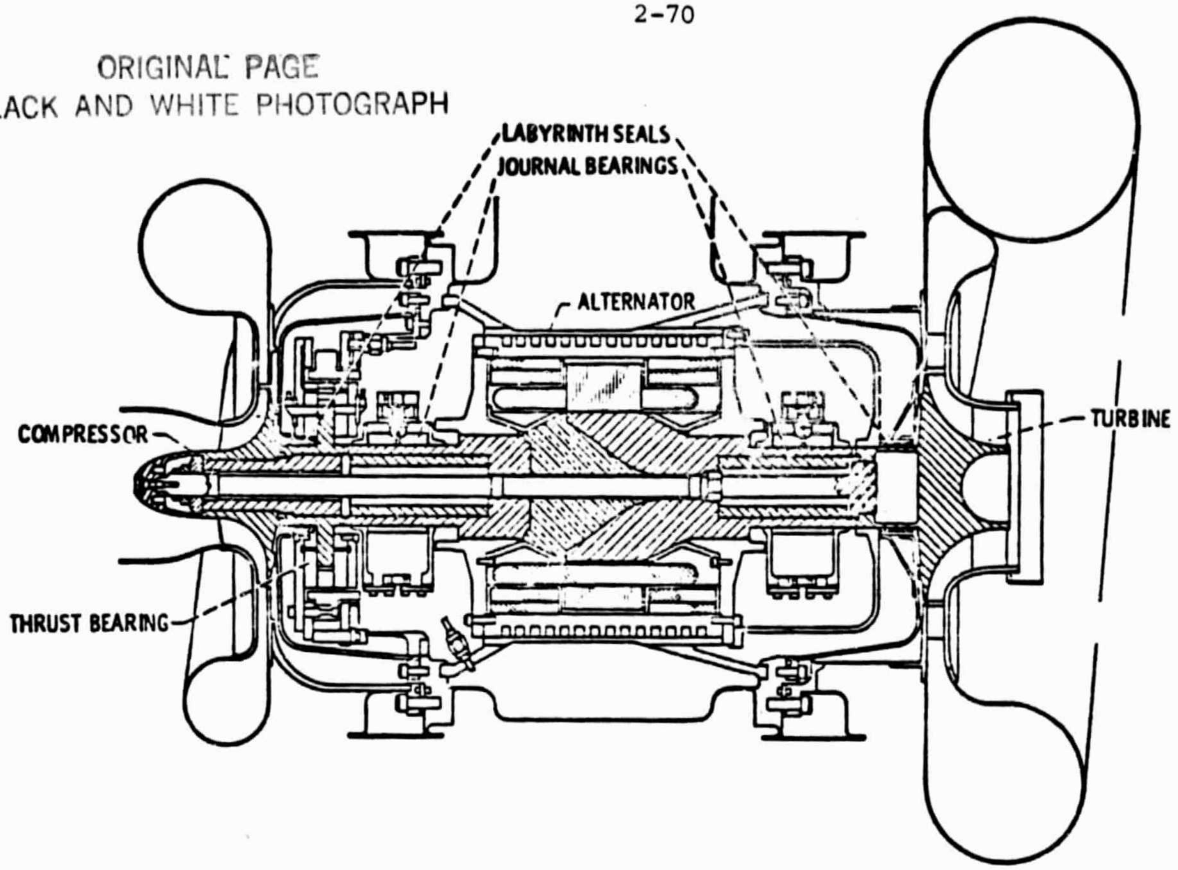

Figure 2.24 (a). Brayton Rotating Unit Cross-Section of Main Components. (Reference 68)

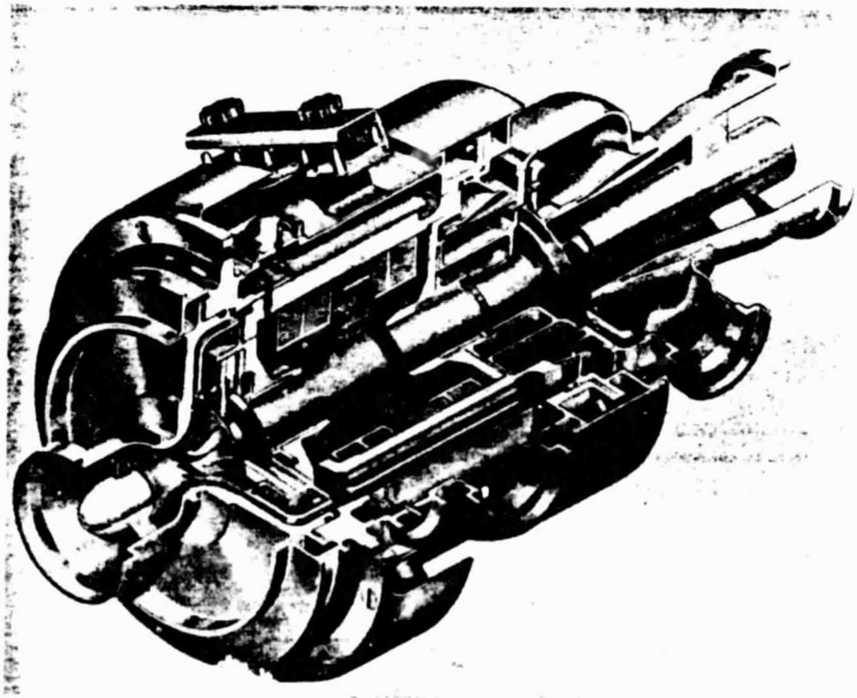

Figure 2.24 (b). Mini-BRU Cutaway. (Reference 69)

The other critical element of these units is the recuperators, which must operate at the turbine exhaust temperature to help reheat the high pressure working fluids. These devices have been built and operated with the rotating units described above as a complete system. The recuperators have a design effectiveness of 0.90, with pressure losses of 0.09 psi and 0.05 psi on the turbine outlet (hot) and compressor outlet (cold) sides, respectively, using type 347 Stainless Steel. The corresponding gas temperatures were: 1110 °K (turbine inlet) and 420 °K (compressor outlet). The design shown in Figure 2.25 is typical of recuperators built and tested, and is a multi-pass, cross-counterflow heat exchanger.[72] Higher effectiveness (i.e., .95) recuperators have also been tested at lower power throughput.

RANKINE CYCLE TURBINES

Rankine cycles have also been designed, built, and tested for space operation. These have utilized organic working fluids, mercury, and alkali metals. The SNAP 8 development program conducted by NASA in the mid-1960s and early 1970s investigated solar powered mercury Rankine cycles in the power range of 35 to 90 kW_e.[73] These systems operated at pressures of 250 psia and temperatures of 1250 °F (950 °K) for 10,000 hours without significant deterioration. A tantalum tube boiler was used to insure wetted-wall contact with the mercury. Higher temperature, larger alkali metal Rankine power components were also built and tested in conjunction with the space nuclear power program.[73] These devices were driven by radioisotope source and, in some cases, by fast fission reactors designed for high powers. Potassium was the most common working fluid; rubidium and cesium were also considered. Peak temperatures of approximately 1600 °F (1150 °K) were obtained in these turbines with successful use of refractory metals in the blades and stators and corrosion resistant seals, bearings, and heat exchanger materials elsewhere in the system. Astroloy U-700 and refractory alloys such as TZM molybdenum have been tested for potassium turbine blades, and HA-25 alloy was used for hot stage nozzle vanes. The alloy T-111 was tested as a principal structural material in flow passages; ASTAR-811C is an attractive alternative to T-111 and can be fabricated more

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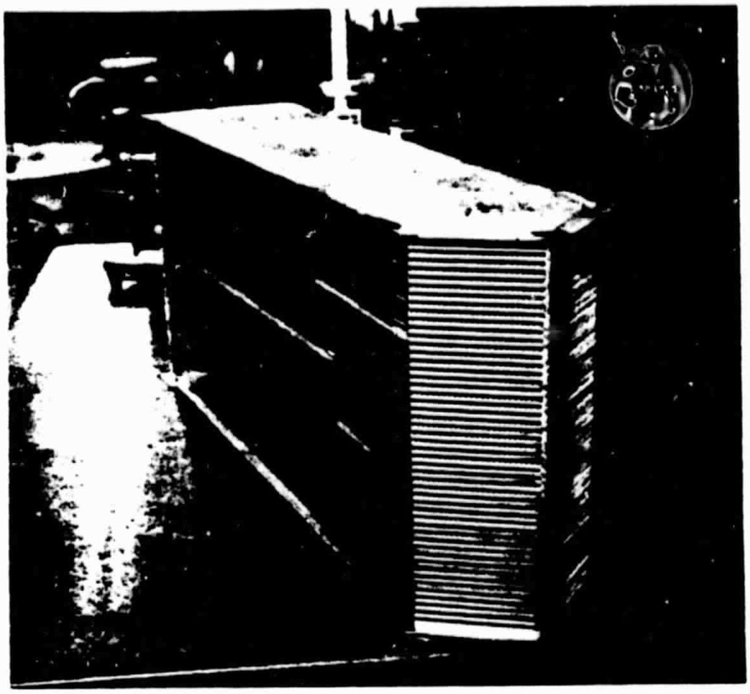

Figure 2.25 (a). Mini-Brayton Recuperator Core Assembly. (Reference 72)

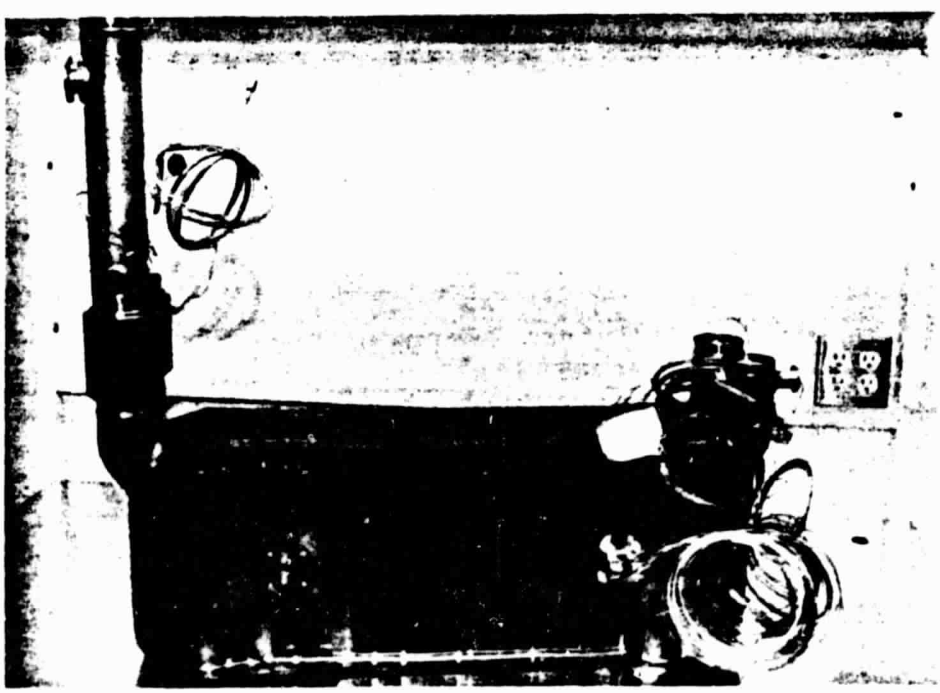

Figure 2.25 (b). Mini-Brayton Recuperator Configured for BIPS Workhorse Loop. (Reference 72)

easily. These systems were aimed at spacecraft power on the order of 450 kW_e. Heat was to be transferred into the cycle at 2150 °F (1450 °K) and to be rejected at 1200 °F (920 °K) to minimize radiator weight. The internal pressures ranged from 163 psia at the turbine inlet to 5.4 psia at the radiator/condensor. Figure 2.26 shows several examples of the Rankine cycle turbines tested under this program. Approximately 800,000 hours collectively were spent in testing potassium Rankine cycle components and over 23,000 hours on cesium components.

2.2.4 Limits to Present Technology

The best performance characteristics of current flight-tested photovoltaic cell and radioisotope thermoelectric conversion systems are summarized in Table 2.12 as benchmarks for energy conversion technologies. Through continued development of these technologies, an evolutionary increase in performance can be expected. These evolutionary improvements are discussed below and quantified when data is available. Any new or advanced concepts must exceed one or more of the benchmark characteristics for energy converters by a large amount in order to provide a significant increase in performance over the evolutionary improvements in performance.

Specifically, in experimental silicon flat arrays, a power-specific mass of about 16 g/W BOL has been attained.[74] Also, on experimental silicon solar cells, efficiencies near 18% Air Mass 1 (about 16% Air Mass 0) have been reported.[75] Theoretical analyses indicate that Air Mass 0 efficiencies near 20% might ultimately be attainable.[76] Whether such high efficiency cells can be prepared with equal or better radiation resistance than current cells is still an open question. In contrast, advanced thin silicon solar cells of rather high efficiency have been prepared with approximately twice the useful life of the current production cells, namely a power output of 0.86 of the original power output after irradiation with 1 MeV electron to a fluence of 3×10^{14} cm^2.[49]

Significant work has earlier been carried out with "p on n" Si solar cells containing Li in the base region. These cells exhibit annealing of radiation damage at normal cell operating temperatures. The cells,

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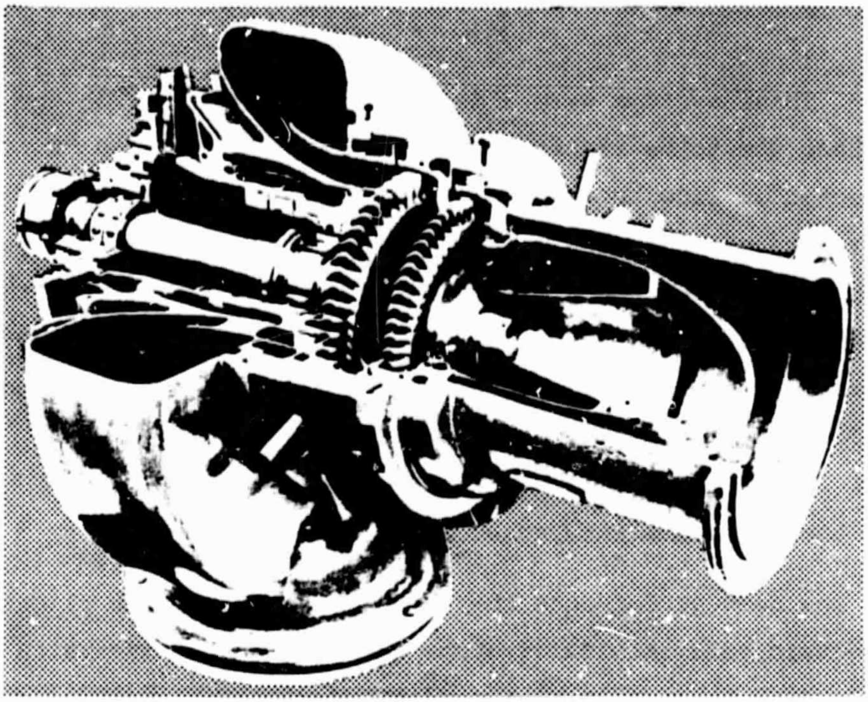
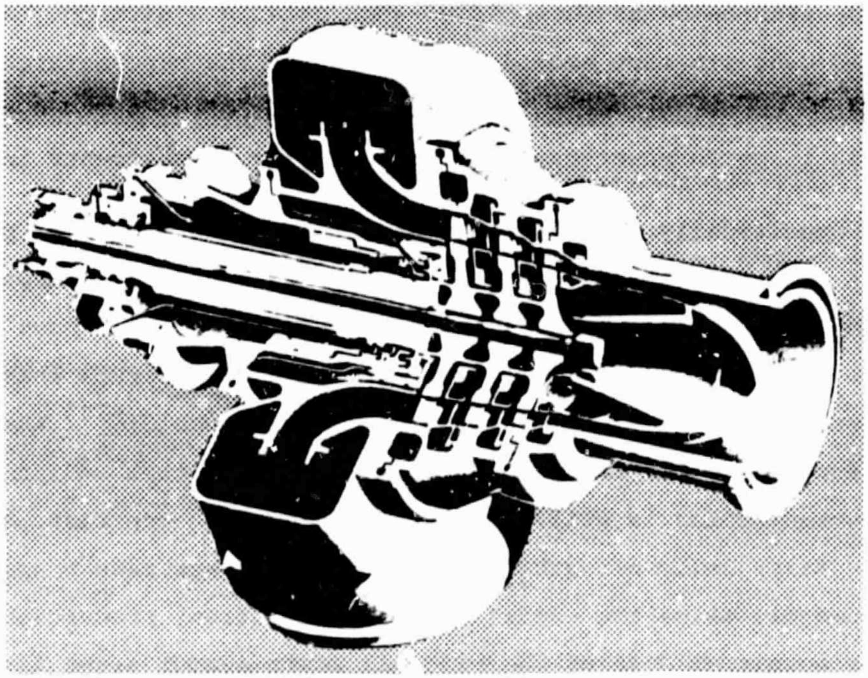


(a) Two-stage Potassium Vapor Turbine.



(b) Three-stage Potassium Test Turbine.

Figure 2.26. Potassium Vapor Turbines (adapted from Reference 73).

Table 2.12

Energy Converter System Benchmarks

	η	Power Specific Mass
Photovoltaic Cells (Silicon Flat Arrays)	14.5 %	15-60 g/W(e)
Thermoelectric (with RTG source)	6.4 %	330 g/W(e)

however, also showed some instability, and their advantage over the normal "n on p" Si solar cells in an electron radiation environment was not adequate to warrant further development.

In cognizance of the large effort mounted under the DOE program towards the reduction of the price of terrestrial solar cells, NASA has set a goal for the power-specific price of $30 $/W for silicon flat arrays. It appears that this goal applies to the arrays themselves, without deployment mechanisms. [See Section 2.1 for a discussion of deployable arrays.] These efforts in progress on silicon flat arrays towards mass and price reduction with efficiency improvement and further radiation hardening need to be maintained in the further NASA and DOD programs since they represent a relatively low-cost, low-risk evolutionary approach with reasonably defined goals.

More advanced photovoltaic cell concepts, including GaAs cells, MIS/SIS cell structures, tandem and vertical multi-junction structures, multi-bandgap systems, and other novel photocell concepts are assessed in Section 2.2.7. These concepts suggest a variety of ways of improving on the basic flat silicon photovoltaic cell performance by virtue of using different materials and configurations better matched to the solar spectrum, able to operate at higher temperatures without serious loss of efficiency, and/or relying on focused sunlight.

Improvement of the overall thermoelectric converter design to reduce specific mass and incorporate new heat sources while retaining the basic unicouple or thermoelectric element (Figure 2.27) is being studied.[77] Modification of the basic SiGe material to reduce its thermal conductivity and thereby increase its efficiency is also underway. This effort is emphasizing GaP additions to the basic SiGe material.[78] Both of the above result in small increases in performance which are sufficient to meet immediate mission requirements.

In brief, the limits to performance of present thermoelectric converter approaches is tied to the peak temperatures obtainable with insulating materials now in use and by the techniques employed for

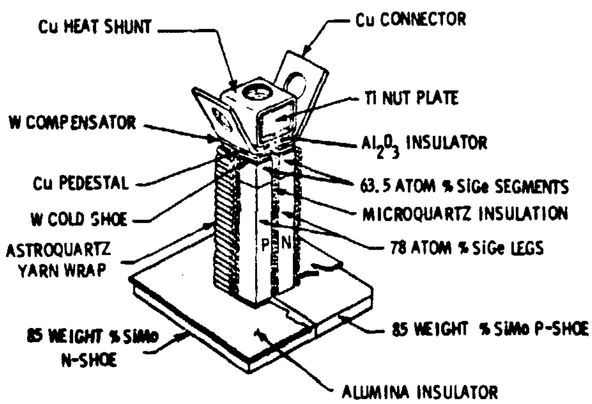


Figure 2.27. Thermoelectric Element (Unicouple).
(Reference 77)

transferring heat within the system (i.e., thermal conduction). These limit the project efficiency of SiGe thermoelectric converters to approximately 12% when operated at temperatures up to 1950 ^{o}F (1340 ^{o}K); an incremental reduction in power-specific mass down to 40 g/W(e) for solar powered systems (i.e., no batteries) or 168 g/W(e) with radioisotopes is also considered feasible as a result of the systems development occurring concurrently.

Thermionic energy converter (TEC) research has and is presently emphasizing electrode materials development or designs which would increase the efficiency or performance of the converters.(79) Increased surface area associated with grooves or surface roughness formed during fabrication has been tried and evaluated. Incorporation of two materials with different work functions into the electrode surfaces has also been evaluated(80) as have additions such as oxygen to form controlled surface oxides. Limited improvements in efficiency on the order of a few percent have been achieved by these techniques.

Major gains are theoretically available if 1) a low work function collector material could be maintained at a sufficiently low temperature to limit back emission from the collector, or 2) electrodes operating principally with inert gas plasmas in devices containing a third electrode were to be developed.(81) Continuing efforts along these lines have shown limited progress in converting these concepts to practical devices.

Performance reference values for present technology are set at 10% overall efficiency (i.e., including lead and system losses), a power density of 4 to 8 W/cm^2 with output voltages in much the same range (i.e., 0.5 to 0.7 Volts) as operating devices. An estimate for power-specific masses for a space-qualified 200 kW(e) system using thermionic energy conversion with 10% efficiency is 40 kg/kW.(82)

It is interesting to note that this 10% efficient 200 kWe conversion system, a propulsion system, and a 3 tonne payload which can be placed into LEO by the shuttle can subsequently reach Saturn or Uranus within a 10 year

period. Higher efficiencies (e.g., on the order of 15%) would enable similar mission constraints to be met for exploring Neptune and beyond.

The limits to Brayton cycle turbine energy conversion performance depend on the gradual extension of turbine blade and heat exchanger materials to higher temperatures to improve the cycle efficiency and reduce radiator weight as well as an improvement in the reliability of turbine systems. Blade metallurgy has been developing continuously toward higher temperature operation. Figure 2.28 shows the creep strength of a variety of blade materials in various stages of development and use. The horizontal dashed line indicates an approximate criterion for material acceptance for turbine tip speeds of approximately 250 m/sec (820 ft/sec); the height of the dashed line is proportional to tip speed squared. Above the dashed line, materials will survive with less than 1% creep for more than 40,000 hours at the temperatures and tip speed indicated. Materials such as Nickel based alloys are in use now for larger turbines. Experimental turbines have been built and tested for many of the niobium (i.e., columbium) alloys, tantalum alloys, and molybdenum alloys.(68,69) Small (e.g., 50 kW or less) ceramic turbines have also been constructed which encounter the highest cycle temperatures (i.e., 1600 °K or 2400 °F).(83) In the near-term we anticipate that blade temperatures of 2200 °F (i.e., 1500 °K) could be made available in a fully developed Brayton cycle system using tantalum alloys.(69) This would permit thermal cycle efficiencies on the order of 37%. This assumes a mean radiator temperature of 450 °K and some temperatures on the order of 1600 °K. An overall power-specific mass can be estimated from a recent study of nuclear Brayton-powered propulsion systems, giving a value of approximately 14.4 kg/kW(e) for a 400 kW_e unit.(84) This specific weight excludes the reactor and shielding masses, but does include two separate Brayton units, heat exchangers, recuperators, and radiator. Each unit is capable of delivering the full power; a single unit system would be 7.2 kg/kW(e) under the same assumptions.(84)

The use of multiple units is directly related to the reliability of individual power modules. Single units are subject to single point failure

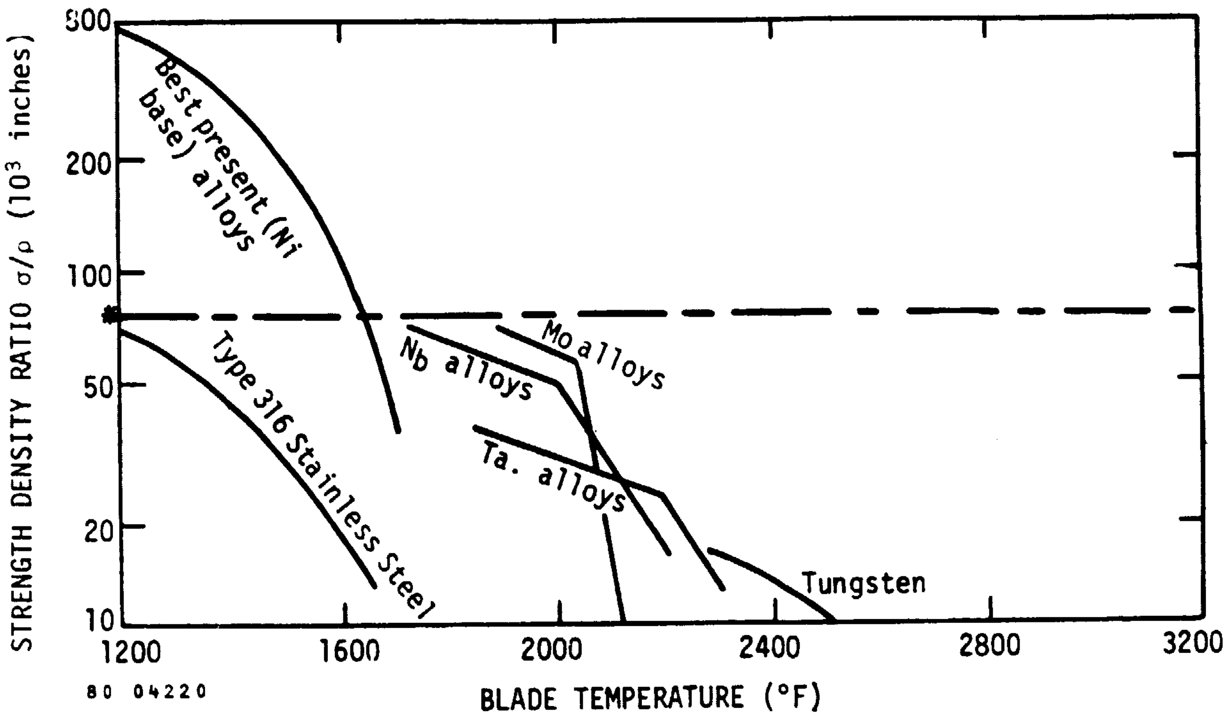


Figure 2.28. Gas Turbine Blade Materials. Strength-density ratio (σ/ρ) plotted against temperature for various materials. Dashed line (*) at 80 x 10^3 inches represents a typical σ/ρ requirement for long life in axial-flow turbine.

and, as such, are generally unacceptable. For moderate to high powers (e.g., 100 kWe to 1,000 kWe), multiple units each supplying only a fraction of the total power can be used to increase the overall system-wide reliability. For example, if the reliability of each turbine power unit is 95% for the mission lifetime and 100 such units are used, then there would be only one chance in 1000 that the power output would ever be less than 95% of the rated power of the system, assuming that 10% excess capacity was originally installed.(85) At smaller total system power, this approach is not as attractive because turbine unit efficiency falls and power-specific mass rises substantially as the unit size decreases (e.g., see Figure 2.23).

A similar analysis naturally applies to the Rankine cycle turbine power system. Molybdenum alloy turbines may achieve 1470 ^{o}K (2200 ^{o}F) operating temperatures in potassium vapor under the constraints discussed above for turbine blade stresses. This constitutes 100 ^{o}K higher temperatures than those where long duration creep tests (i.e., 10,000 hours) have been conducted.(71) Higher temperatures also are accompanied by increased material migration within the potassium loop, especially as impurity levels of dissolved materials increase over the lifetime of the mission. The use of CrAl alloy claddings is being investigated in combustion applications as added protection to reduce alkali metal salts attack of stronger substrates in turbine blading.(86) A cladding substrate approach might also prove feasible for achieving high turbine temperatures in the pure alkali metal vapor environment of a space Rankine cycle. These developments should lead to a Rankine cycle efficiency on the order of 19% (with a power-specific mass of 5 kg/kW(e) at the 375 kW_e size, excluding the radiator), making it strongly competitive with Brayton cycle systems.(24) The efficiency in this case, while low compared to the Brayton cycle, does permit low radiator weight advantages of a high reject heat temperature (i.e., 900 ^{o}K or 1160 ^{o}F).

2.2.5 Basis of Comparison

Energy conversion systems can be compared fairly on the basis of their power-specific mass, reliability over a fixed period of time (i.e., probability that the power level will not drop more than 10 percent below rated power capacity during the mission lifetime), and cost per kW(e), if available. The preceding section has discussed the limits to the performance which can be expected from an evolutionary development of present energy conversion technology. The benchmarks of Table 2.12 indicate the best systems which have been flight tested. The current photovoltaic cell technology has demonstrated approximately 25 kWe with certainty. The reliability for a 10 year mission may be obtained from the photovoltaic cells as well as the thermoelectric units (e.g., those used in the Voyager series where nearly 85% of peak power is still available after 7 years). Henceforth, these select figures will serve as benchmarks to judge disparate, advanced, or new energy conversion technologies. Overall system efficiency also is relevant in special circumstances where the absolute size of the collector and/or radiator associated with the conversion system becomes a hindrance; for example, in orbital transfer propulsion applications where atmospheric drag is significant or in situations where scaling to larger sizes entails an increase in power-specific mass of the radiator or collector per se.

2.2.6 Applicability to Generic Missions

Generally, thermal energy conversion systems can be used for any mission since either solar or nuclear energy may be utilized. Photovoltaic energy conversion, restricted to the use of solar energy, will be applicable to the missions with an adequate solar source, as indicated in Table 2.7 of Section 2.1.

2.2.7 Advanced Conversion Technology Assessment

A great variety of advanced conversion concepts have been proposed which promise improvements over present conversion technologies. Some of these appear to be prosaic extensions of current development with rather

modest increases in performance. Other concepts are still just ideas with very little concrete data for evaluating their claims. There are an interesting number of novel schemes promising significant performance improvement and having sufficient data to back up these projections. This last class of advanced conversion concepts encompasses new ideas in both photovoltaic and thermal energy conversion areas. The more advanced, novel concepts are also reviewed and data needs, if any, are noted.

2.2.7.1 Advanced Photovoltaic Conversion

Advanced development in photovoltaic conversion encompasses the use of compound semiconductors such as GaAs, heterojunction devices, multi-bandgap cells, MIS/SIS cells, and tandem junction as well as multi-junction cell structures. Other photon-assisted conversion concepts (e.g., photon-assisted electrolysis) are assessed in Section 2.2.7.3 under Novel Concepts.

The main thrusts of advanced photovoltaic cell development are to improve cell performance, enhance radiation resistance, select better methods of support and encapsulation, realize the potential of higher solar concentration ratio effects, derive higher voltages, and achieve *in situ* annealing. These concepts, along with structural and other material improvements, aim at increasing cell life and reducing power-specific mass.

GaAs SOLAR CELLS

A flat array currently under development is based on Gallium Arsenide (GaAs) solar cells. The more successful of these cells are of the $GaAl_xAs_{1-x}/GaAs$ wide bandgap window layer structure. The effort is primarily directed at developing cells of lower mass (thin film devices) and possibly greater operating life (that is, of higher radiation resistance) than is obtainable in silicon solar cells. The solar cell efficiency will be comparable to or possibly slightly higher than that obtainable in silicon solar cells. In elevated temperature operation the

GaAs solar cells exhibit a significant efficiency advantage over the Si cells.

Efficiencies of 15 to 17% Air Mass 0 have been reported[87] for single crystal GaAs cells of relatively large thickness and, consequently, high mass (the density of GaAs is about 2.5 times higher than that of Si), and test groups of such cells have been successfully flown on spacecraft. The operating life advantage of these devices is, however, still in question.[87,88]

There has been some evidence that annealing of radiation damage may occur in single crystal GaAs cells at temperatures near 150 ^{o}C. It may thus be possible to experience no significant performance degradation by high temperature operation of these cells. The evidence for this is, however, not yet complete.

True thin film, polycrystalline GaAs solar cells have now been reported with efficiencies near 10%.[89] A goal for the power-specific mass for the GaAs cells is 10 to 40 g/W, and the power-specific price is expected to fall into the 300 to 1500 $/W range. These estimates are summarized in Table 2.13.

Because of the performance advantages of the GaAs cells under high temperature operation, these cells are thought to be better suited for use with optical concentrators. Here a power-specific mass of 5 g/W is projected for the complete concentrator/array system. Since the efficiency of properly designed solar cells increases with light intensity, a solar cell efficiency of 18% under operating conditions with optical concentration is expected to be achieved on such systems. However, there exists very little experience with the deployment and performance of optical concentrators in space, so that most of these data are projections. While waste heat rejection in space is a problem at higher irradiance, it is thought advantageous rather than to use one or a few large-area concentrators with the corresponding photovoltaic converters, to break the system up into a large number of small-area concentrators with very small photovoltaic converters, possibly not much larger than a common

Table 2.13

Technology Basis for GaAs Photovoltaic Arrays

Item Assessed	Units	Experimental GaAs Flat Array	Experimental GaAs Concentr. Array
Power-Specific Mass	g/W	10-40	5
Power-Specific Price	$/W	300-1500	-
Experience Base (total flown)	kWe	Test groups only	-
Array Efficiency	%	~14	-
Solar Cell Efficiency	%	15-17	18

integrated circuit chip. This approach might possibly also bring cost advantages for the concentrator fabrication.

MIS/SIS SOLAR CELLS STRUCTURES

Development efforts are in progress, particularly in the terrestrial program, to replace the commonly used potential barrier, a pn-junction, by one resulting from a MIS or SIS structure. The development of these cells has been pursued primarily under the viewpoint of potential lower-cost processing compared to pn-junction formation, but this premise is being increasingly questioned. In a few cases efficiencies comparable to those obtained in pn-junction devices have been achieved.[90] However, the structure contains an insulator of 20 to 50 Angstrom thickness which is sensitive to environmental influences. While this might cause degradation in the pre-launch environment, the charged-oxide layers have also been found to be extremely vulnerable in the space radiation environment.

In addition, the higher efficiency MIS or SIS solar cells are now understood to operate as minority carrier devices, just as the pn-junction solar cells. Thus, they are also subject to radiation damage by minority carrier lifetime reduction, besides the charge buildup in the insulator layer. Also, the insulator layer and the space charge region below it are even closer to the device surface than the depletion region of a pn-junction cell, so that low energy protons could have a large effect. Without a recognized efficiency advantage and with the potential reliability and radiation damage problems, the MIS/SIS solar cells do not seem to hold much promise for an advanced photovoltaic space power system at this time.

TANDEM AND VERTICAL MULTI-JUNCTION STRUCTURES

In the conventional solar cell structures, a single potential barrier - usually a pn-junction or, as in recent developmental cells, an MIS or SIS barrier structure - is located in a layer parallel to the light exposed surface, usually at a very small distance from the latter. Recently, experimentation with so-called tandem junction cells has been

carried out in which a second potential barrier, or pn-junction, is placed nearer to the back, Ohmic contact of the device. So far efficiencies near those obtained for single junction devices have been achieved in these cells.[91]

In vertical multi-junction (VMJ) cells the potential barriers are placed normal to the light exposed surface instead of the usual parallel placement. They have been experimented with primarily in silicon. A number of variations are possible for the VMJ cell. They include cells in which the junctions reach all the way through the thickness of the cell. In others they reach only part way from either the front or the back surface into the cell. The latter arrangements require, by necessity, a parallel connection of the multiple p and n regions. The advantage of VMJ cells lies primarily in the potential attainment of a higher radiation resistance. However, this increased radiation resistance can be achieved only if the individual p and n regions are made very thin compared to a diffusion length.[92] This requires a structure of very thin individual layers, which are difficult to reproduce with current process technology. This type of structure has been better approximated in the parallel junction VMJ cells than in the series junction VMJ cells. Consequently, the improved radiation resistance has so far been observed only in the former.

On the other hand, a series connection of the individual cells which are represented by each p and n region pair, including a pn-junction, leads to a cell which produces a low current and a high voltage. At the same time, the structure is so arranged that the series resistance is naturally small. For both reasons, a cell with high voltage and low current lends itself especially well for use with high concentration ratio optical concentrators. It should be noted, however, that such a cell is much more sensitive to variations in irradiance over its light exposed surface than a single, parallel junction cell would be.

From theoretical considerations, significant efficiency advantages for either tandem junction or VMJ cells cannot be expected over conventional parallel junction cells of comparable material, structure, and optimal design. However, the VMJ approach does have the advantages of combining high efficiency with increased radiation resistance and, in the series connected version, coupling with low series resistance and higher voltages, making it attractive for high ratio optical concentrator applications.

OTHER SOLAR CELLS

The only other type of solar cell which has been test flown on spacecraft is the copper-sulfide/cadmium-sulfide (Cu_2S/CdS) thin film solar cell. Because of its relatively low efficiency (3 to 7%) and stability problems, this cell has not been considered as a viable candidate for photovoltaic space power systems for over ten years. However, a variation of this design, using Cu_2InSe on CdS, has recently been shown to achieve better efficiency and stability.

While numerous semiconducting materials of properties suitable for photovoltaic solar energy conversion exist, none of these materials is known to have attributes which could make it significantly more favorable by itself for spacecraft power systems than the materials developed so far; that is, silicon and gallium arsenide. Therefore, it does not seem warranted, at least at this time, to expend the considerable research and development effort necessary to bring the technology of newer materials to a state comparable to that already achieved for silicon and gallium arsenide. In general, it cannot be expected that efficiencies significantly above 20% Air Mass 0, without optical concentration, can be achieved with any single semiconducting material.(93)

With optical concentration the conversion efficiency of the solar cells themselves may reach into the mid 20% range, but it has to be observed that the optical concentrator also will have a limited efficiency, which may make the complete power system not significantly smaller than a

flat array. It is, however, conceivable that its mass might be lower (e.g., 5 g/W) as well as its price.

MULTI-BANDGAP SYSTEMS

The only way conceived so far for attaining significantly higher efficiencies is by the use of several semiconducting materials with different bandgaps. Two approaches to this end are being pursued. The first involves external optical beam splitting using dichroic elements which direct separate spectral bands of the total solar spectrum to individual solar cells prepared from semiconductors with different bandgaps which are matched to the particular optical spectral band.[94] The second approach utilizes the optical properties of the semiconductors of different bandgaps for the beam splitting. Here the cells are mounted behind each other in the optical path of the sunlight so that each can respond to its most favorable wavelength range. The latter approach goes under the name of "stacked cells," "tandem cells," "cascade cells," "multicolor cell system," etc.[95-97] In such stacks the cell with the widest bandgap faces the incident radiation, while the cells with successively smaller bandgaps are mounted in sequence behind. For systems with adequately large numbers of such cells of different bandgap, theoretical conversion efficiencies above 50% have been computed, while practical efficiencies in the 30 to 40% range may be expected.[95,98]

The problem with these multi-bandgap systems is that each semiconductor material with a particular bandgap has to have its own potential barrier (usually a pn-junction) and has to be connected to the neighboring cells by a transition layer which exhibits the properties of an Ohmic contact. At the same time, the transition layer should be optically nearly perfectly transparent to all wavelengths not absorbed in the preceding cells in the stack. This means that practically the entire cell interface area shall be transparent, with negligible absorption on reflectance. This requirement eliminates the more conventional cell connection with metallic Ohmic contacts, except possibly if applied in a grid pattern. New approaches have consequently been pursued, such as using

a heavily doped layer of either or both of the two different materials for the transition layer and making this layer adequately thin to permit tunneling of the charge carriers through the resulting potential barrier. Such transition layers are known under the name "tunnel junctions."[96,97] A second approach is to use the newly developed "super lattices" for the transition layer.[99] Such a super lattice consists of a periodic structure of alternating layers of different bandgap or different impurity content.

So far, in Air Mass 1 sunlight, efficiencies of approximately 28% have been attained with multi-bandgap systems using optical beam splitting by dichroic elements,[100] and approximately 16% with stacked cell systems using tunnel junctions.[96] The development of these systems is actively pursued by the Air Force and the terrestrial photovoltaics program of DOE. While the optical beam splitting systems can be readily attained with current technology, successful development of the stacked cell system will require a substantial effort.

The optical beam splitting systems are mechanically more cumbersome to implement, while the stacked cell system seems to provide a more elegant approach. Either system is expected to be, at least initially, relatively expensive. It will, therefore, appear to be more attractive in use with optical concentrating systems, particularly those of high concentration ratio. In addition, the efficiency of the multi-bandgap systems is expected to increase significantly with higher solar irradiance so that the use with concentrators appears advantageous also from the performance viewpoint. By combination with concentrators, multi-bandgap systems are already practical with two or three junctions. The availability of high efficiency photovoltaic converters will make the application of concentrator systems much more attractive since the optical collecting area, viz. the concentrator size, needed for the satisfaction of a given load can be significantly decreased by use of high efficiency converters. This decreased collector area makes the use of relatively costly high ratio concentrators much more attractive than their application with photovoltaic converters of a single semiconductor. On the other hand, it is conceivable

that the stacked cell systems might ultimately be produced cheaply enough to make them also attractive for flat arrays.

A disadvantage of the multi-bandgap system is that changes in operating conditions (spectral distribution, light intensity, operating temperature, performance degradation) can cause a mismatch betwen the individual cells of the system and, consequently, an efficiency loss should the cells be connected in series. It may, therefore, be advisable to connect each cell of the system to its own load circuit (power conditioning system); however, this would entail additional system complexity, cost, and probably mass.

In summary, the photovoltaic conversion concept promising the greatest performance advancement is the multi-bandgap system in the stacked cell version or, alternately, with external optical beam splitting. The multi-bandgap systems may be instrumental to making optical concentration practical in space. Less ambitious, but nevertheless important, development concepts involve improved radiation resistance (including annealing techniques), better encapsulation where electrostatic bonding is being developed as an alternative to the common adhesive bonding techniques, the development of high concentration ratio and of higher operating temperature solar cells (e.g., GaAs), and improvement of single and vertical multi-junction cells for better efficiency, particularly through higher voltage. Most of these concepts are already being pursued to some degree within NASA or DOD and through the DOE program. However, there is a need for considerable further development effort in each of these areas to help achieve the desired performance improvements.

There is a real need for a careful study of the relative advantages of photovoltaic concentrator systems versus flat photovoltaic arrays. Each of these has been evaluated in its own right, but there is not sufficient data on comparable performance conditions to allow a clear selection of the best approach. Also, many approaches have been tried in the past which have not been very successful to date, for example, in increasing radiation resistance; but the problems are still there, and it is important to continue to seek solutions for them.

2.2.7.2 Advanced Thermal Energy Conversion Concepts

Advanced thermal conversion concepts have been suggested in the areas of thermoelectrics, thermionics, and thermal dynamic converters. These concepts span ideas which have a long history and which may be fruitful now because of new materials or the use of new configurations as well as relatively new ideas for which virtually no data exist for their evaluation. Advanced thermal conversion concepts generally offer the potential for higher efficiency than photovoltaic converters with the associated problems of greater complexity. The greatest uncertainty concerns the overall power-specific mass associated with the whole system, including heat source (or collector) and waste heat radiator. Within the limits of material strength, power-specific mass will be reduced by devices which operate at the highest temperatures possible in order to reduce the waste heat radiator mass. Advanced radiator concepts are presented in Section 2.4. Novel concepts involving thermal and direct photon energy conversion are treated in the next section (2.2.7.3).

ADVANCED THERMOELECTRIC CONVERTERS

New Materials

Development and demonstration of a new thermoelectric system typically requires 10 years of research effort. In some cases, such as the selenide system, problems become apparent only after long-term testing in the system configuration. These problems can be related to material evaporation, interdiffusion, creep deformation, diffusion caused by current flow, or a wide spectrum of other problems. Thus, research is needed as a continuing effort on new or promising systems to document not only short-term performance but long-term degradation mechanisms.

As discussed above, thermoelectric conversion at higher temperatures has the advantage of reducing power system mass (e.g., radiator mass). As temperatures are increased, electrical insulation problems must either (1) be avoided by using radiation heat transfer from the heat source to the hot side of the converter, or (2) addressed by an insulator development program. Existing data indicate that electrolysis is a major mechanism for

insulator deterioration in the +1000 °C range. furthermore, there is a specific need for higher temperature thermoelectric materials themselves. High temperature materials including the chrome-lanthanum-chalcogenide system (Cr_2Se_3, La_2Se_3, and La_2S_3),[101] the Si-C system,[102] the B-N system, and others are currently being evaluated. Little data is available on these systems at present. However, it is understood that these materials generally degrade more rapidly via the mechanisms cited above as the temperatures increase. They also suffer from loss of structural integrity if they are subject to thermal cycling under load (i.e., compressive stresses); for example, if the heat source is solar energy.

The payoff in terms of power-specific mass is directly related to higher operating temperatures. For example, increasing the operating temperature from 1000 °K (SiGe alloys) to 1300 °K (e.g., rare earth chalcogenides) can reduce the radiator weight by a factor of five, assuming a constant temperature difference of 570 °K between hot and cold junctions; that is, the radiator temperature would be increased from 430 °K to 730 °K.

Alkali Metal Thermoelectric Converter (AMTEC)

This is a relatively new direct conversion concept[103] in which an alkali metal (sodium) is driven around a closed thermodynamic cycle between two heat reservoirs at different temperatures and pressures (i.e., 1 atm and 10^{-2} atm) as shown in Figure 2.29. This device does not rely on the Seebeck effect. Rather, the principal step in the cycle consists of the separation of sodium into positive ions and electrons by means of a beta-alumina solid ionic conductor to produce electrical work. Beta-alumina belongs to the class of materials known as solid electrolytes or fast ion conductors. These materials have ionic conductivities much larger than their electronic conductivities and can thus act as permselective barriers in electrochemical devices. At a temperature of 800 °C, for example, beta-alumina's ionic conductivity is 0.63 $ohm^{-1}cm^{-1}$, while its electronic conductivity is only 0.0023 $ohm^{-1}cm^{-1}$. A porous metal electrode covers the low pressure, cold side of the beta-alumina barrier. Electrical leads

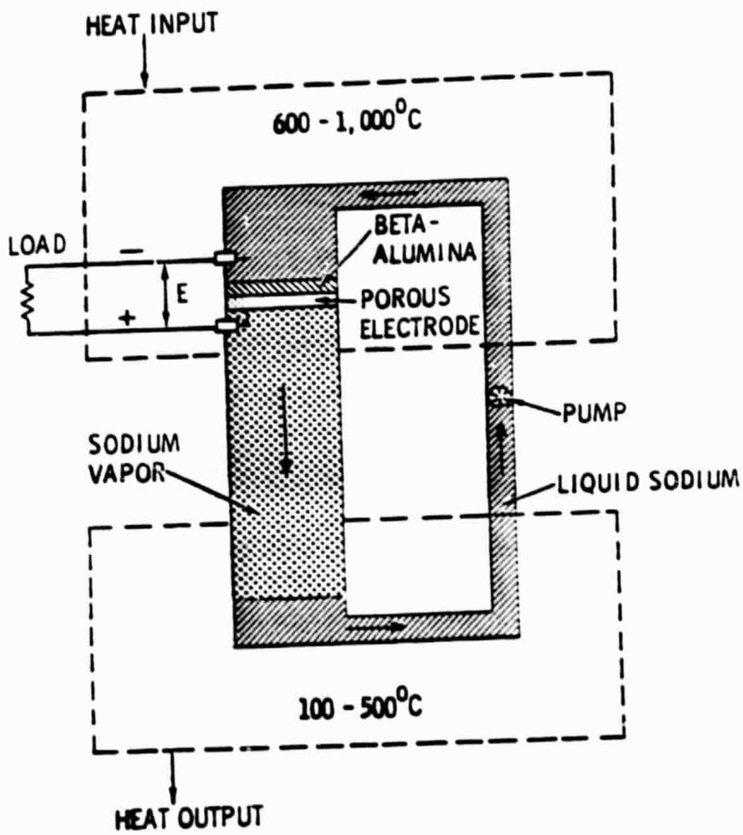


Figure 2.29. Alkali Metal Thermoelectric Converter Schematic (Reference 103).

making contact with the porous electrode and the high temperature liquid sodium exit through the wall of the device. Nearly all of the temperature drop (i.e., 500 ^{o}K) across the AMTEC occurs in the low pressure vapor space between the porous electrode and the outer wall. A return line and an electromagnetic pump circulate the sodium working fluid through the AMTEC.

At the beginning of the cycle, cold sodium from the condenser enters the hot zone (Figure 2.29) and absorbs thermal energy until it reaches T_2. The temperature enhanced pressure differential across the beta-alumina forces Na^+ ions across the ionic conductor, stripping the electrons off in the hot liquid sodium phase, and recombining them with the ions at a lower potential in the porous electrode on the cold side by connecting the two sides of the beta-alumina with an external load-bearing circuit. Thus, a voltage potential gradient is established in the beta-alumina which is given ideally by

$$V = \frac{RT_2}{F} \ln\left(\frac{P_2}{P_1}\right)$$

where T_2 is the heat source temperature, F is a Faraday, and P_1 and P_2 are high and low pressures creating the pressure gradient. This voltage can produce work in the external circuit.

As current flow increases, the voltage decreases (Figure 2.30) due to two effects: 1) An IR drop occurs across the ionic resistance of the solid electrolyte, and 2) the pressure at the electrode/electrolyte interface increases so as to drive sodium vapor through the electrode and across the vapor space. The voltages obtained from the AMTEC are comparable to those from single battery cells (e.g., 1 to 1.5 volts).

The efficiency of the AMTEC under realistic conditions must take into account the thermodynamic efficiency plus the effect of parasitic heat losses from the high temperature to low temperature regions. These heat losses consist of heat conduction through the structure and electrical leads, and the thermal radiation (infrared) from the high temperature electrode surface to the low temperature condenser. For an estimate of upper limit efficiency, it can be shown that:

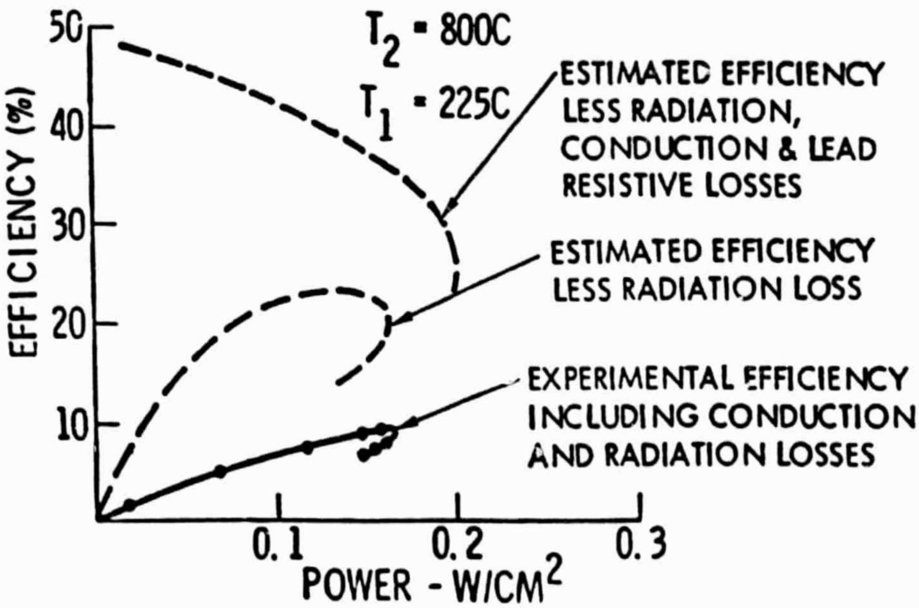


Figure 2.30. Efficiency versus Power Density for the Alkali Metal Thermoelectric Converter (Reference 103).

$$\eta_{max} \sim 50\% \sim 0.9\ \eta_{Carnot}$$

Figure 2.30 shows the actual measured efficiencies for an experimental AMTEC. Also presented are calculated efficiencies based on the reduction of parasitic losses, thus showing the potential for improvement in future AMTEC design and operating characteristics. With high temperature series connection and optimized radiation shielding, the efficiency of the AMTEC should rise to the 20% ~ 40% range.

Based upon the present level of experience and understanding of AMTEC operation, a small AMTEC power module using a radioisotope heat source ($Pu^{238}O_2$ fuel) with a maximum surface temperature of 1100 ^oC and a reject temperature of 300 ^oC would have an efficiency of 25%. The specific power of the projected AMTEC conversion system is 21.5 W(e)/kg for a 1000 watt output. The present projections for the lifetime characteristics of such an AMTEC system indicate that, after approximately 10,000 hours, the output power would be reduced by 50% or the specific power would decrease to approximately 11 W(e)/kg. However, it is anticipated that these lifecycle characteristics can be improved substantially with further research and development. The AMTEC could also be integrated with a solar concentrator heat source.

Other Thermoelectric Converters

A variety of unusual direct conversion heat engines have been proposed which rely on cyclic thermal processes which induce voltage potentials via hysterisis effects, for example, in ferroelectric materials.(104) Typically, these concepts are limited to modest temperature (i.e., room temperature to 200 ^oC) and small temperature differences. A very limited amount of experimental data is available at this time, which makes their use for space power systems difficult to evaluate. They do show promise for high power per unit volume. Current research in this area is being supported by the Department of Energy. New higher temperature versions of this concept would be required before it shows any significant promise for advanced energy conversion.

Thermogalvanic cells, similar in many respects to the AMTEC device, have also been proposed. These cells develop a voltage between two electrodes as the result of the transfer of a liquid between the two electrodes which is brought about by electrochemical reactions at the electrode/electrolyte interface and ionic transport in the electrolyte.[105] The higher temperature versions of this concept have used molten salts and solid electrolytes. The reactions are driven by applying heat to a hot electrode and removing heat from the colder electrode. Generally, these have not been as successful as the sodium/beta-alumina cell.

ADVANCED THERMIONIC ENERGY CONVERTERS (TEC)

Areas where modest performance gains are available and where production of a practical device appears feasible are combined TEC-thermoelectric (TE) converters and the particle converter. The combined TEC/TE utilizes a thermoelectric material as the electrical leads, which are the series connectors between the hot thermionic emitter of one converter and the cooler collector of the next converter in the series string. The temperature differential is capable of producing sufficient power in the T/E material to offset the I^2R power loss produced by the current flow. One would expect an increase in efficiency to 19% from this approach.

The particle converter shown in Figure 2.31 requires low work function particles (e.g., porous metal oxides) with low thermal conductivity to replace cesium in the interelectrode gap.[106] These devices can be viewed as thermoelectric devices with a large Seebeck coefficient and a high figure of merit. Output powers of 60 mW/cm^2 appear feasible when operated at emitter temperatures of 1370 ^oK. Evaporation of the particulate filler still appears to be a problem. The peak efficiencies anticipated for this type of converter are 20%; current devices appear capable of achieving 12 to 16% in a laboratory environment.

The slow, but steady, progress of TEC technology has resulted in long life devices with usable output, usable efficiency, and the advantage of high heat rejection temperatures for space power conversion if the high

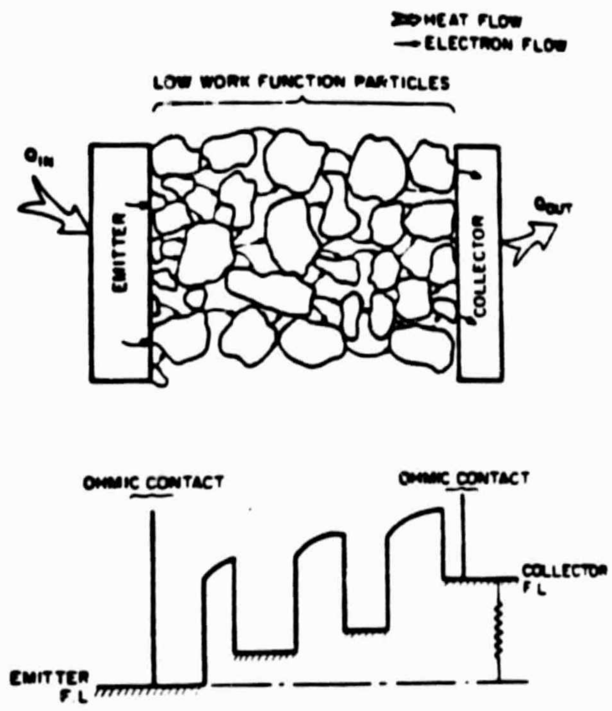


Figure 2.31. Schematic Representation and Motive Diagram of Particle Thermionic/Thermoelectric Power Converter. (Reference 106)

temperature supporting technology can be developed. Both T/E and TEC systems need high temperature heat sources and high temperature insulators. For example, silicon carbide and cermet electrodes made of ZrO_2 and Mo, which are being developed for combustion fired systems, may also work well in space power systems.[107,108] These material requirements are more severe for TEC than for TE because of the higher operating temperatures for TEC.

Concepts have been proposed to eliminate the high temperature insulator by utilizing the electrical resistivity of long heat pipes supplying heat to the conversion units.[109] Approaches of this type reduce design flexibility somewhat, require operation of the system at a maximum of 5 to 10 volts to maintain acceptable parasitic losses, and have yet to be demonstrated as operating hardware. Demonstration of the uninsulated system as a parallel effort to research on insulated systems appears merited if it can be shown there are distinctive power-specific mass advantages to this approach.

Heat pipes of moderate length which can be bent are needed on the hot side of both TEC and thermoelectric systems to couple converters to proposed nuclear heat sources. Similarly, heat pipes of unusual geometry are needed to reject heat to a radiator.

The above research needs are in addition to the ongoing research program to develop low work function collectors and low cesium pressure diodes or triodes. Demonstration of lifetime as well as performance of TEC devices is required to provide credibility to continued research in this area. Evaluation of combined TEC/TE devices and the particle converter concept also appear merited.

HIGH TEMPERATURE EXPANDERS

To take full advantage of the potential of thermal dynamic systems (e.g., Brayton and Rankine cycles), expanders need to be developed which can withstand higher peak temperatures. This development can proceed along two fronts. The first approach is high temperature materials development

for gas turbines, and the second is the development of novel high temperature expander concepts which do not require substantially new materials. The latter category includes MHD generators, free piston expanders, and energy exchangers, each of which bypass the critical problems of high tip speed stresses combined with high temperatures that plague gas turbine development. Furthermore, these novel expanders span the range of power scaling from medium power (free piston expanders), medium to high power (energy exchanger), to very high power (MHD generators). Within this power range there is considerable overlap in the applicability of these three concepts. It is important to note also that each of these ideas offers substantial payoff without substantial risk in development based on the existing technology base. The consequence of this fact plus current support for these technologies outside of NASA is that high temperature thermal power systems have a choice of expanders; the most crucial problems are, therefore, how to generate the high temperatures and how to radiate the waste heat effectively.

ADVANCED GAS TURBINE DEVELOPMENT

New turbine blade materials are being investigated which have the potential for higher temperature operation. These are principally ceramics being developed in conjunction with the automotive gas turbine program and high temperature refractory alloys being developed for military gas turbines and for high temperature, combined cycle power plant operation. Some ceramic-coated metal blade combinations are also under development.

Much of this development must also deal with corrosion and erosion as well as high temperatures, since the applications involve combustion gases with excess air, corrosive combustion products, and, in some cases, particulates. Generally, closed cycle operation - such as the space power application - is a less demanding materials environment. Materials which are resilient at high temperatures but which oxidize readily may have been disregarded in the current development program. Such materials would possibly be suitable for the space application, and they need to be re-examined in this light.

The ceramics under study include silicon carbide and silicon nitride. These are meant to be used as uncooled rotor blades, often with an integral ceramic disk to which the blades are attached, and, sometimes in larger devices, attached to a metal disk. Ceramic coatings now being studied include ZrO_2 stabilized with Y_2O_3 sprayed onto a MCrAlY (where M=Ni or Ni/Co) substrate which covers the refractory metal blade (e.g., Udimet-500).[110] These coatings performed well in clean fuels at 2000 °F. Aluminide coatings worked at temperatures up to 2100 °F.[111] Ceramic blade attachment to metal rotors has been attempted. For example, the blade can be dovetailed to an intermediate superalloy piece which in turn is attached to a metal disk.[110] In this design a compliant surface minimizes the stresses where the ceramic blade is attached. Hot pressed, fully dense Si_3N_4 was used for this design, which operates at 2500 °F inlet temperature, 2275 °F blade temperature, and approximately 4850 rpm in the 30 MW power level. Surface flows related to the smoothness of the surface finish, especially on the blade root, had a strong predictable correlation with spin test failures. Sialons (compounds of silicon, aluminum, oxygen, and nitrogen) may also prove to be suitable for high temperature turbine applications.

Figure 2.32 shows the 1% creep stress at 40,000 hours (horizontal line) for a variety of turbine materials as a function of blade temperature. The ceramics, as discussed above, have the potential for extending peak turbine blade temperatures from the benchmark value of 1500 °K up to 1520 °K. The cobalt and nickel based metal alloys have already been surpassed by the tantalum and molybdenum alloys which, in turn, have set the benchmark value.

We conclude that Brayton cycle temperatures may be increased from 1600 °K (2400 °F) to 1650 °K (2500 °F) by using ceramic blades and either a ceramic (integral) rotor disk in small units or a metal (or two metal) disk for large units. This results in efficiency increases from the benchmark (37%) to 38%, a relatively small increment in performance and a possible reduction of only 12% in the radiator weight.

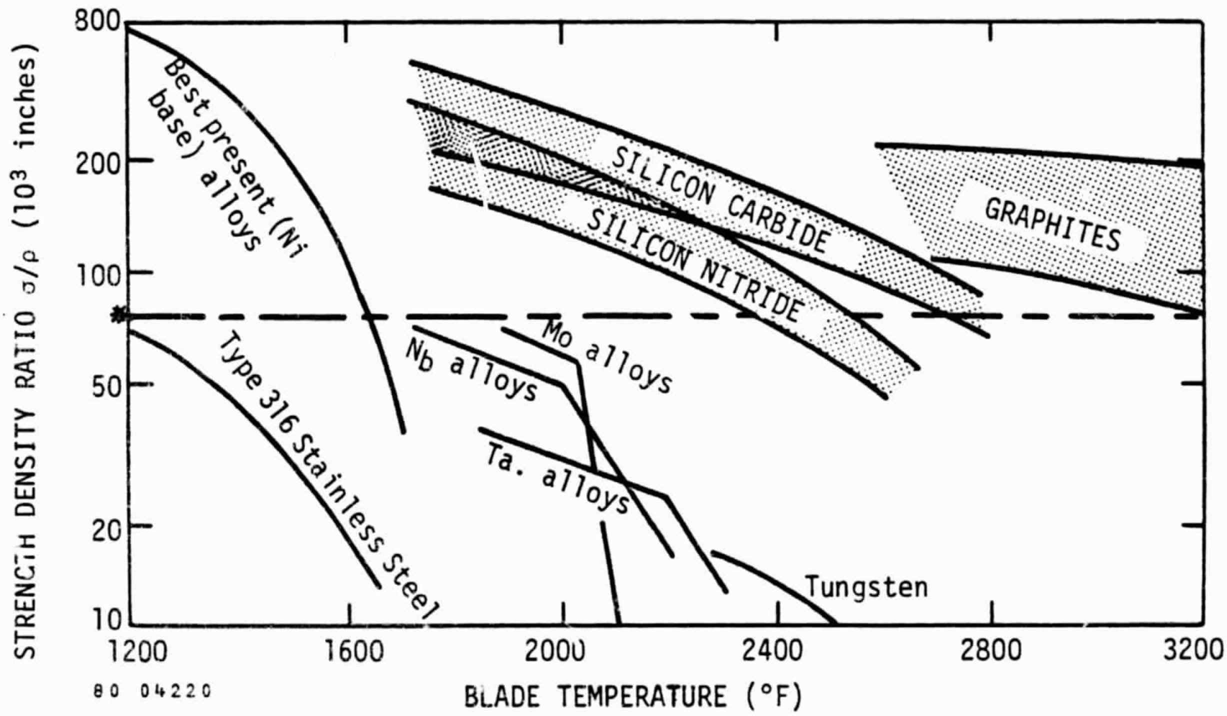


Figure 2.32. Gas Turbine Blade Materials. Strength-density ratio (σ/ρ) plotted against temperature for various materials. Dashed line (*) at 80 x 10^3 inches represents a typical σ/ρ requirement for long life in axial-flow turbine. Si_3N_4 and SiC have temperature advantage of 800 to 900° over the best nickel-based alloys.

FREE PISTON EXPANDER

Free piston expanders are of interest for space power systems because of their potential ability to operate at substantially higher coolant temperatures than turbines can.

The free piston expander (Figure 2.33) would be driven by an expanding high temperature, high pressure coolant (e.g., argon or cesium vapor). The energy of expansion would then be directly converted to electricity in an external coil by flux displacement caused by the moving high conductivity piston. The piston would not contract the wall of the expansion chamber but would be magnetically or gasdynamically suspended.

The power cycle would be equivalent to a conventional closed Brayton cycle with a turbo-compressor, except that the turbine would be replaced by the reciprocating piston. Two power strokes would be delivered for each cycle of the piston, with flow controlled by appropriate valving. The expanded gas would be pushed from the chamber on the return stroke into the flow line for delivery to the compressor. A rotary turbo-compressor is indicated in Figure 2.33; it is the simplest and lightest compressor, and the blade temperatures are compatible with present state-of-the-art materials. A separate reciprocating piston compressor could be used, or compression could even be carried out on the return stroke of the expander. System weight and efficiency considerations appear to rule against such systems, however. Separate compressor/expander devices also are readily compatible with heat recuperation, which increases cycle efficiency.

The piston would be made of a refractory metal (e.g., Mo) and would operate at a temperature about halfway between the inlet and outlet gas temperatures. Assuming 3000 ^{O}K for the inlet and 1500 ^{O}K for the outlet, the average piston temperature would then be 2250 ^{O}K. Molbydenum pistons appear satisfactory under these conditions.

For efficient power generation the magnetic Reynolds number of the piston ($R_m = \mu_o Va$) should be $\gg 1$. For typical velocities of ~100 m/sec and

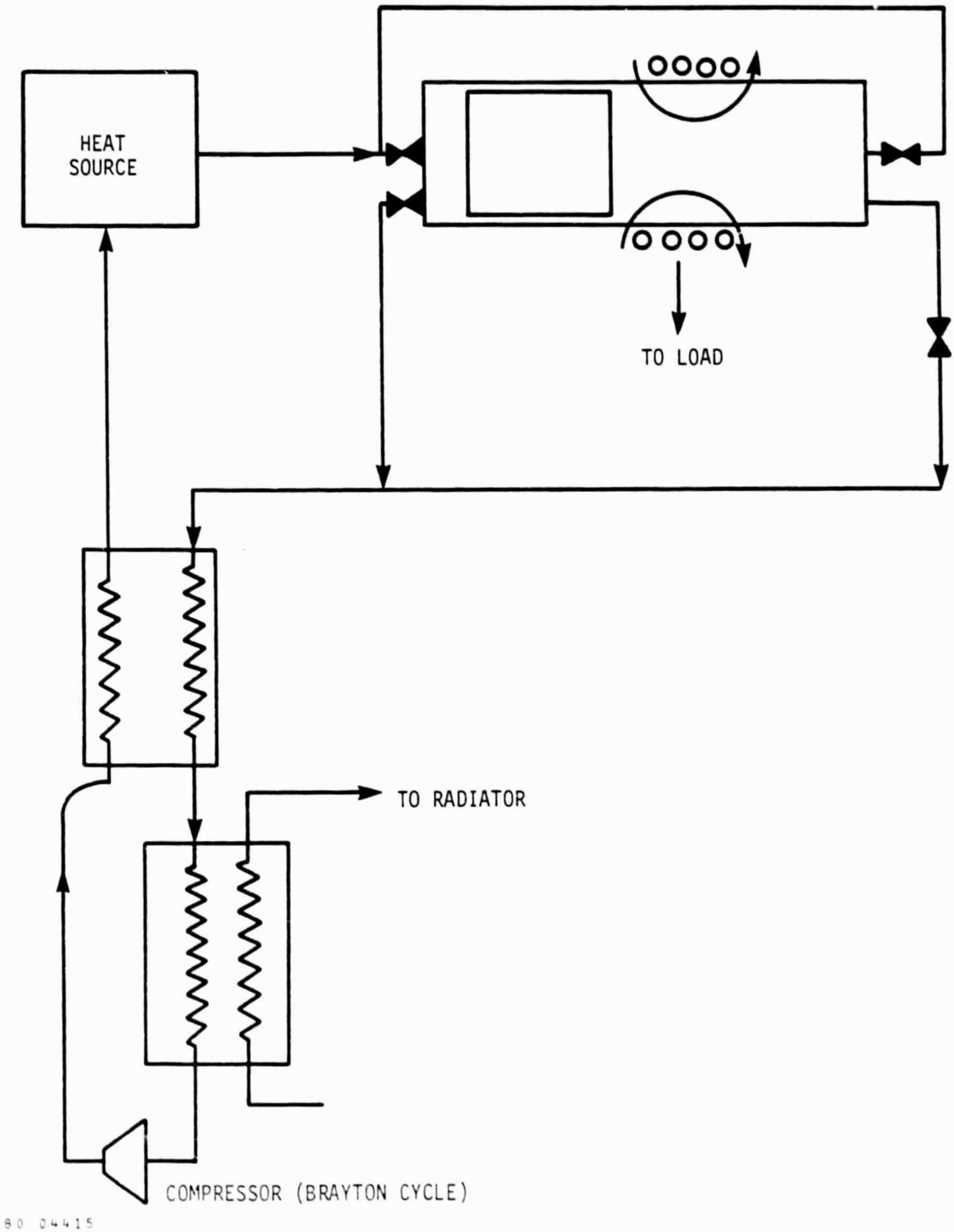


Figure 2.33. Free Piston Expander.

piston diameters of 0.3 meter, R_m for a molybdenum piston is on the order of 10, which appears adequate for efficient power generation.

Illustrative performance parameters are shown in Table 2.14 for an inert gas working fluid (e.g., argon). High working pressures are favored for compact, high power output.

A radial clearance of 0.2 cm is chosen, which permits some gas blow-by during the stroke. This can be minimized by using a high molecular weight working fluid (argon) and shaping the surface of the piston to reduce the velocity of the gas that leads through the gap between piston and chamber wall. One can use the equivalent of non-contact rings on the piston to make the gas go through a series of expansions and contractions as it flows down the gap. The 5% blow-by value corresponds to an effective gas velocity through the gas of one-tenth of sound speed, which should be readily achievable.

Overall cycle efficiency for the example in Figure 2.33 is ~30% with a power output of 3 MW(e). The expander chamber is quite small (30 cm diameter, 150 cm long) and would be very light in weight.

The molybdenum piston could be hollowed out with rib supports if desired, although piston weight is small. Detailed design studies would be required for a realistic determination of expander system mass, though a range of ~0.1 to 0.2 kg/KW(e) appears reasonable (300 to 600 kg for a 3 MW(e) system).

Although there has been a substantial amount of work on free piston engines, primarily of the combustion driven type, considerable R & D would be required to develop a free piston expander for space power generation. This R & D would primarily relate to components (high temperature valves, power conversion circuits, piston materials) and control (load control of piston motion, suspension dynamics). There appear to be no fundamental go/no go issues, however.

Table 2.14

Free Piston Expander Illustrative Performance

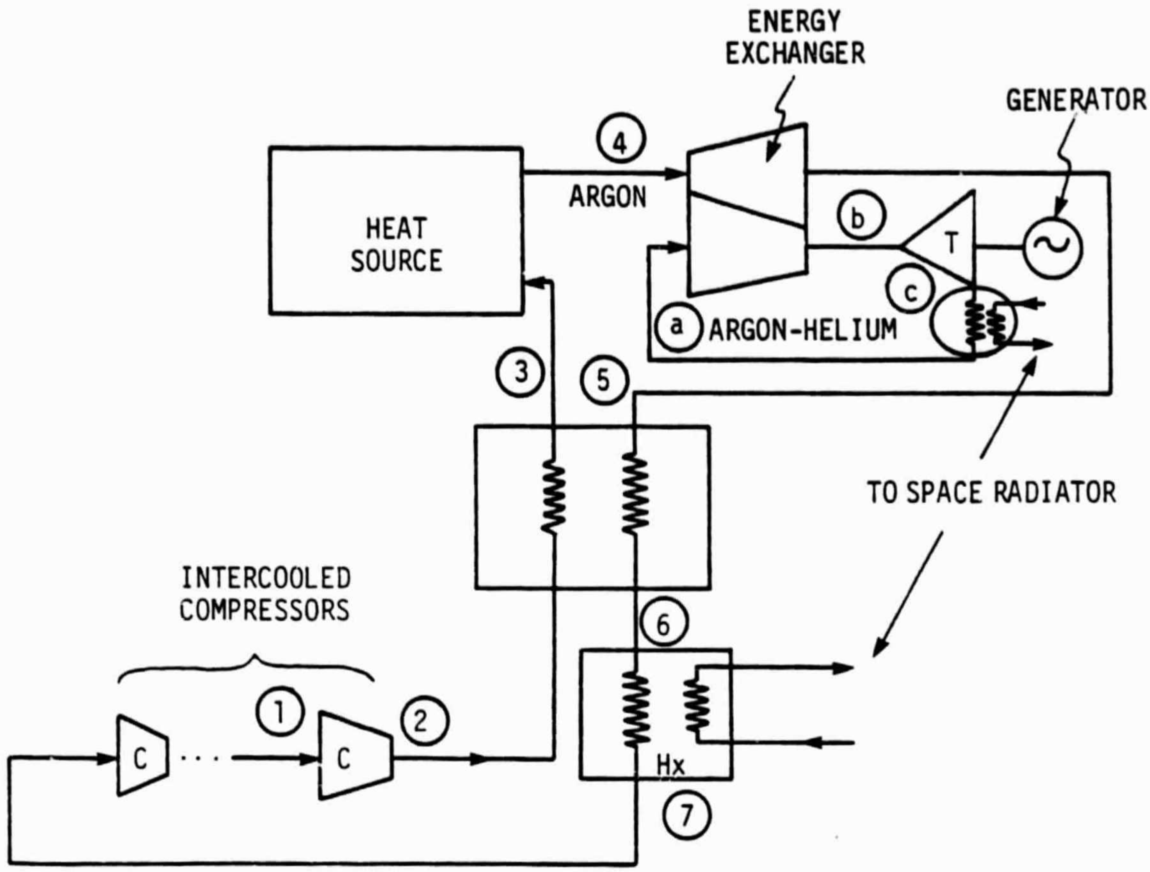
- Argon Working Fluid
  - ~1000 psia inlet pressure
  - ~3000 °K inlet temperature
- Molybdenum Piston
  - L/D ~1
  - ~30 cm diameter
- Piston Frequency ~30 Hz
- Volume Expansion Ratio ~3/1
- Expander Length ~1.5 meters
- Intake Volume ~25 liters per stroke
- Average Velocity ~70 meters/sec
- Radial Clearance ~0.2 cm
- Gas Blow-by ~5%
- Output Power ~3 MW(e)
- Net Cycle Efficiency ~30%
- Radiator Temperature ~900 °K

ENERGY EXCHANGERS

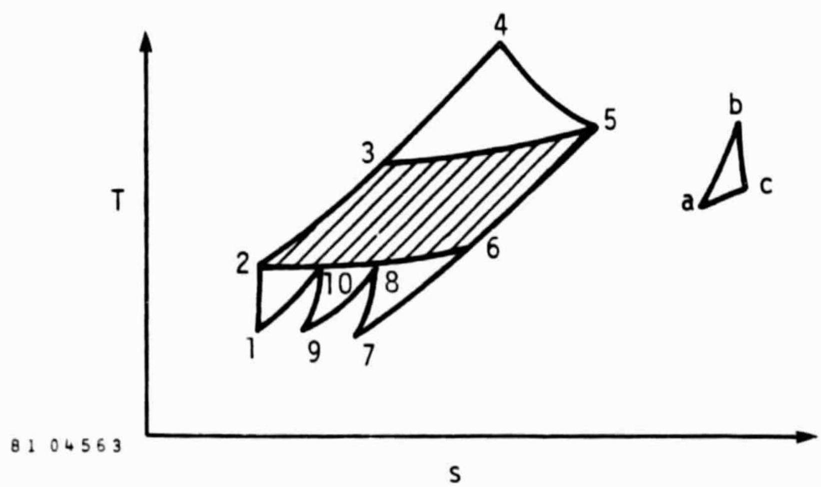
Energy exchangers combine the high temperature capabilities of piston type expanders with the ability to maintain steady flow.

The energy exchanger (Figure 2.34a) would also be driven by a high temperature, high pressure working fluid such as argon or alkali metal vapor. A second, lighter molecular weight working fluid such as an argon-helium mixture would be compressed in the energy exchanger by the driver gas and exhausted at high pressure but lower temperature to a conventional uncooled turbine for work extraction. Consequently, very high temperature thermal cycles (e.g., Brayton or Rankine) are conceivable with the use of the energy exchanger. Such cycles must operate either as topping cycles to more conventional lower temperature power cycles or as recuperated (i.e., Brayton) cycles where the heat left in the energy exchanger exhaust is re-invested in the heating portion of the cycle (see Figure 2.34b).

Energy exchanger technology has reached a commercial level of application for diesel superchargers, and it is currently being developed by DOE for application to electric power generation systems.[112] The latest series of experiments using argon and argon-helium mixtures have demonstrated good work transfer efficiencies on a small (100 kW_{th}) device with projected efficiencies in the 80 to 85% range for fully engineered versions of this device.[113] These component efficiencies are high enough to warrant further investigation of higher temperature and higher pressure versions of the energy exchanger. The key problems are to maintain good seals with efficient aerodynamic design at the elevated temperatures and pressures desired, and to utilize the higher temperature waste heat effectively in the power cycle. High temperature operation appears feasible with present materials, vastly simplifying the development process required. Inlet (i.e., peak cycle) temperatures on the order of 2000 $^{\circ}K$ (i.e., 3150 $^{\circ}F$) appear feasible for most gas environments, since the rotor temperature would be no more than 1500 $^{\circ}K$. These peak temperatures allow an increase in Brayton cycle efficiency from the benchmark of 37% to 43% or, alternately, an increase in radiator temperature from 450 $^{\circ}K$ to 560 $^{\circ}K$, assuming a constant efficiency. This would reduce the power-specific mass



(a) Cycle Configuration



(b) Cycle Thermodynamics

Figure 2.34. Advanced Energy Exchanger/Turbine Brayton Cycle with Intercoolers and Recuperators.

to the 8 kg/kW(e) range. Typical operating parameters are given in Table 2.15.

MAGNETOHYDRODYNAMIC GENERATORS

MHD has been under development for almost three decades in the United States and abroad. The total MHD budget during this interval is on the order of a billion dollars. Many U.S. groups have engaged in MHD work, including AVCO, GE, Westinghouse, NASA, DOE, University of Montana, University of Tennessee, MIT, JPL, ANL, etc.

Most of the work (~90%) on MHD has concentrated on open cycle combustion fired systems using either coal, oil, gas, or solid propellant (military applications) fuel. Although this system is not viable for space power applications, it shares many common development issues with closed cycle MHD systems so that progress in this area helps other areas.

The USSR has been operating a relatively large experimental MHD power plant (the U-25 plant) since 1971 with natural gas fuel. Peak generation powers of ~20 MWe have been achieved using the ANL 5 Tesla superconducting magnet. The U.S. is constructing a relatively large experimental MHD generator in Montana (CDIP) which will be operational relatively soon. Design studies of a demonstration MHD plant are being carried out.

Technical problems have been encountered with MHD channels, air preheaters, and seed recovery units, particularly for coal fired systems with high ash content. The superconducting magnets, while not yet within present state of the art (large 4 to 6 Tesla dipole magnets of the required size have not yet been built), do not appear to present any fundamental problems.

Materials have been developed that promise channel lifetimes of several thousand hours in coal fired MHD. Platinum coatings have been developed for anodes to protect against corrosion by coal slag. Channel efficiencies (i.e., equivalent to turbine mechanical efficiency) for the sizes tested have demonstrated ~40 to 45%, which are comparable to the

Table 2.15

Typical Energy Exchanger/Turbine Operating Parameters

ENERGY EXCHANGER

- Output Power ~500 kW(e)
- Argon Working Fluid
    - 150 psia inlet pressure
    - 2000 $^{\circ}$K inlet temperature
    - 3:1 pressure ratio
- Tantalum Alloy Rotor
    - 30 cm length
    - 30 cm diameter
    - 1440 $^{\circ}$K skin temperature

TURBINE

- Argon-Helium Working Fluid
    - 150 psia inlet pressure
    - 1500 °K metal temperature
    - 3:1 pressure ratio

RADIATOR TEMPERATURE 560 $^{\circ}$K

NET CYCLE EFFICIENCY 43%

POWER-SPECIFIC MASS 8 kg/kW(e)
(including solar collector and cavity, power unit and radiator)

values predicted by theory. Higher efficiencies, ~75 to 80%, are expected for the larger channels appropriate to MHD power plants. Enthalpy extractions of ~20% of flow energy have been demonstrated in shock tube studies, compared to the ~15% needed for practical MHD power plants.(114) Seed recovery appears solvable but has not yet been demonstrated in large systems.

Projected cycle efficiencies for first generation open cycle MHD/steam plants have dropped to the low 40% level as compared to projected efficiencies in the low 50% level a few years ago. This seems to parallel a general decline in coal/steam power plant efficiencies due to tighter environmental controls. Second generation MHD plant efficiencies should be on the order of 50%.

Relatively little direct work has been done on closed cycle, thermal equilibrium MHD because of the current non-availability of heat sources with working fluid temperatures of ~2500 °K. However, no problems are anticipated with extracting 15 to 20% of the enthalpy flow in equilibrium closed cycle MHD channels at generator efficiencies on the order of 70%.

Substantially more work has been done on closed cycle non-equilibrium MHD since lower working fluid temperatures (on the order of ~2000 °K) are acceptable.(115) These could be provided by advanced gas cooled nuclear reactors or solar thermal power systems.

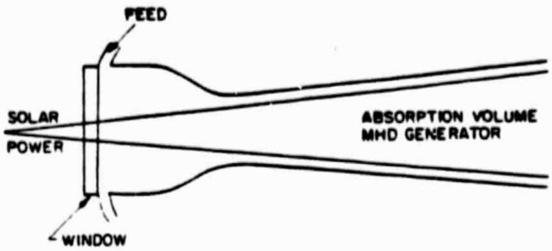
The relatively non-reactive nature of the seeded inert gas working fluid (e.g., seeded argon, helium, or a mixture of argon and helium) greatly eases channel materials problems compared to coal fired MHD systems. Uncooled channels can probably operate up to ~2200 °K and cooled channels well above that.

Initial work on non-equilibrium MHD generators was discouraging since electrothermal ionization instabilities were always observed, which resulted in a spatially non-uniform distribution of ionization and internal current loops that reduced the generator efficiency. GE experiments in the last few years using shock tubes have indicated good generator performance in the non-equilibrium temperature regime if one starts with high initial

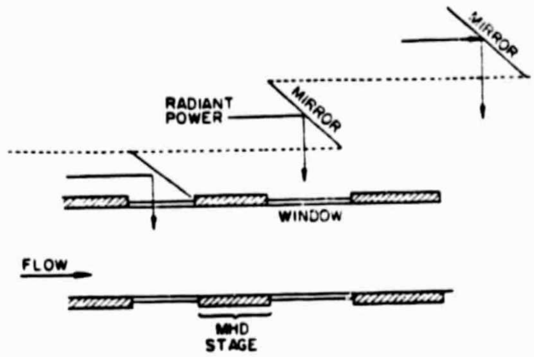
stagnation temperatures.[116] While not conclusive proof of good non-equilibrium operation (ionization relaxation effects may be important), they are encouraging. A U.S.-Netherlands cooperative program should provide conclusive demonstration of a large (5 MWth) non-equilibrium MHD generator in a year or so using a GE MHD channel in the Eindhoven facility.

If successful, non-equilibrium MHD generators will operate at maximum coolant temperatures of ~2000 K. Somewhat lower operating temperatures may be possible, but probably not below 1800 K. The generator should achieve a component efficiency of ~60 to 70% using argon or argon-helium working fluid. The effective Hall parameter ($\omega\tau$) in the generator will be limited to ~2 (even though the microscopic $\omega\tau$ is much larger) by electrothermal instabilities. The low $\omega\tau_{eff}$ is actually of benefit to generator operation since it reduces inter-electrode voltage along the channel and lowers the chance of electrical breakdown. Operating power densities in the channel should exceed 500 MWe per m^3. Several concepts (see Figure 2.35) have been prepared for direct absorption of sunlight into the seeded gas.[117] This technique should allow high temperature operation with cycle efficiencies on the order of 40%. Using a nuclear MHD space power system design,[118] the mass-specific power of the conversion unit is estimated to be 4 kg/kW(e).

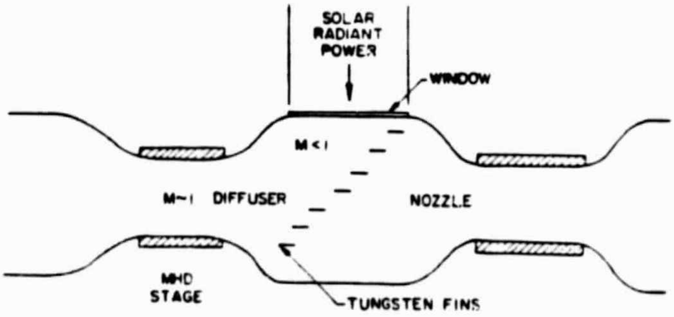
Liquid metal MHD appears to have limited promise for space power applications. Maximum working temperatures are constrained by materials limitations to 1000 °C, while heat rejection temperatures cannot fall too much below this level (e.g., typical radiator temperatures are on the order of 500 to 700 °C) because of radiator mass considerations. The relatively small temperature difference available will result in low cycle efficiency. In addition, liquid metal MHD depends on the expansion of a two phase gas-liquid metal mixture through the MHD channel. The gas component must be recompressed as in a normal Brayton cycle, which tends to reduce efficiency if the available ΔT is small. Experiments with two phase MHD have demonstrated expansion of the mixture, but expansion distances are relatively long (~40 feet in one design for coal combustion plants) to



(a) Aligned flow and radiation absorption in a solar MHD generator.



(b) Staged transverse absorption of radiation alternating with MHD generator stages.



(c) Staged transverse absorption using solid surfaces.

Figure 2.35. MHD Concepts Utilizing Direct Absorption of Sunlight to obtain an approximately isothermal expansion. (Reference 117)

control gas slip past liquid. The relatively low power densities would appear to be unfavorable for space power applications.

In summary, closed cycle equilibrium and non-equilibrium MHD appear to offer considerable promise for space power applications provided nuclear or solar heat sources with high working fluid temperatures in the range of 2000 °K or above prove to be available. MHD physics is well understood, and promising materials for practical channels appear available. However, the efficiency scaling with size suggests that MHD power systems will only be attractive at power levels of 10 to 100 MWe and above. This places the MHD option in the far-term so far as anticipated power requirements are concerned.

HIGH TEMPERATURE RECUPERATORS

Weight, heat exchanger effectiveness, peak material temperature, and size are the most significant features of recuperator design for high temperature Brayton cycle operation. Recuperators for space power systems have been undergoing a continuous evolution in design and materials development over the past twenty years. Figure 2.36 illustrates the temperature limits as a function of allowable stresses for a number of metal heat exchanger alloys.[119] For pressure ratios of 3 to 5 (i.e., for regenerated Brayton cycles) and base pressures of 1 atm, the stress per square inch is on the order of 2 to 4 atmospheres or 30 to 60 psi; at a base pressure of 10 atm, the stresses rise to 300-600 psi. The maximum allowable stress criterion asserts that the true stress be a factor of 10 below the maximum allowable stress. Therefore, those alloys with $(\tau)_{max} \geq 6000$ psi would be satisfactory at the peak pressures anticipated in these examples. These alloys would be viable up to metal temperatures of about 2000 °F (1400 °K), for example, using columbium (niobium).

Ceramics will allow higher material temperatures. The experiment carried out by Garrett[120] and others indicates that temperatures as high as 1530 °K (2300 °F) have been achieved with experimental tube-in-shell silicon carbide and silicon nitride ceramic heat exchangers. Small, rotating ceramic recuperators have been developed for vehicular gas turbine

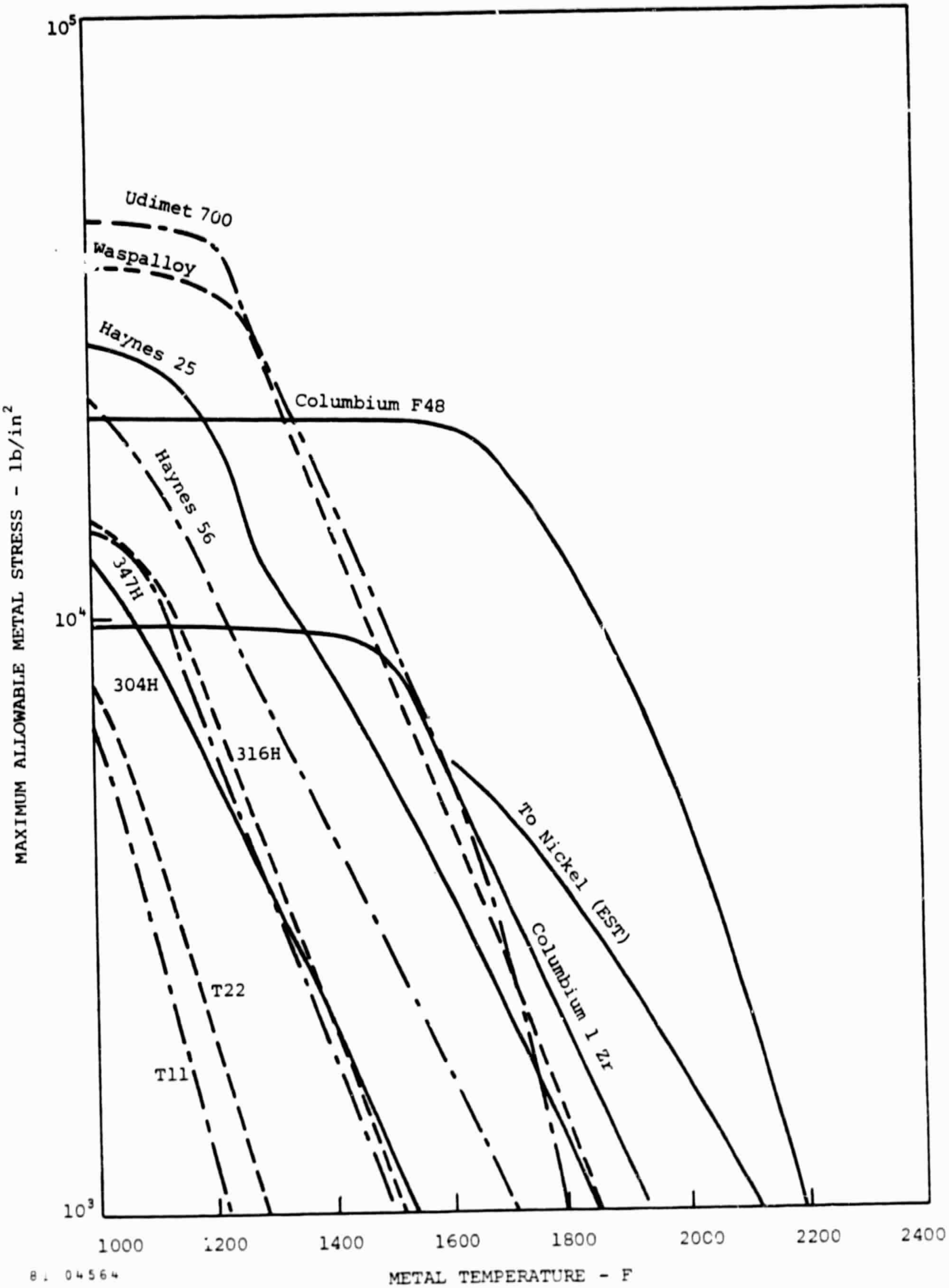


Figure 2.36. Maximum Allowable Stress for Selected Heat Exchanger Material. (Reference 119)

(open cycle) systems in the 60 to 475 kW range.[121] However, there is some question that ceramic heat exchangers will prove practical because of stress and brittle failure problems.

High temperature pebble bed recuperators have operated successfully in many applications. Temperature capabilities well in excess of 2000 °K are achieved using appropriate ceramic materials. However, as presently configured, they are generally large and massive and must be cycled relatively slowly.

Development of a small, lightweight, high performance particulate bed recuperator would be of considerable importance for space power cycles since it would allow high efficiency and high radiator temperature systems. Such recuperators appear feasible using rapid cycling, rotating bed recuperators with small size particulates.

The rotating bed recuperator concept is illustrated in Figure 2.37. A packed bed of small ceramic particulates (diameter of ~100 to 200 microns) is held by centrifugal force inside a rotating porous cylindrical frit. Two beds are used in the cycle, one to extract sensible heat from the low pressure exhaust from the expander and the other to heat the incoming high pressure gas stream from the compressor. The beds alternately carry out both functions, with typical cycle times of ~10 seconds. As shown in Figure 2.37, hot gas from the expander passes down the axis of bed #1 and flows radially out, first through the packed bed and then through the porous cylindrical frit. The exit temperature of the gas is somewhat above the radiator temperature. After heat rejection and compression (two or more stages of compression may be used with radiative heat rejection between compression stages), the cool gas working fluid passes into bed #2, first through the porous cylindrical frit and then radially inward through the packed bed, exiting along the axis of the rotating bed. The hot high pressure gas is further heated by the heat source and then enters the expander.

A linear temperature gradient is established in the packed beds with the highest temperature at the inner surface of the rotating bed and the

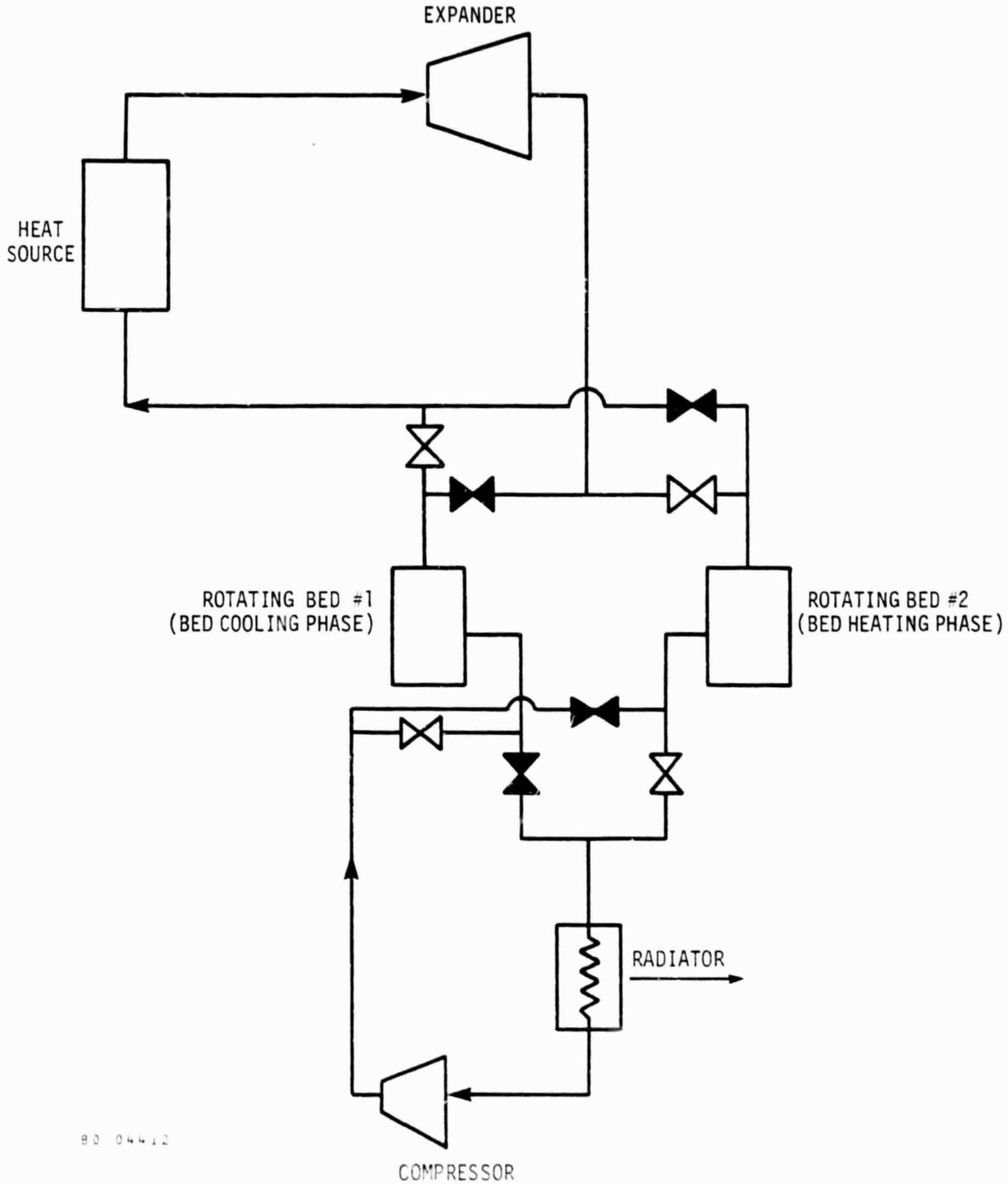


Figure 2.37. Rotating Bed Recuperator.

lowest temperature at the outer surface. Each point in the bed rises by an amount ΔT during the heat extraction part of the cycle, and drops by the same amount during the gas heating phase. There is a small amount of heat leakage to the outside surface of each bed, but the thermal conductivity of the packed bed is low enough that the heat loss can be neglected.

Using low Z ceramic particulates (e.g., graphite or boron carbide), the mass of the recuperator bed can be quite small. For example, with a 20 second cycle (10 seconds heating and 10 seconds cooling) and a ΔT of 100 K, the mass of particulates in the two beds is only 0.10 kg per KW of thermal duty.

The particulate diameter is small enough (~200 microns) that their thermal diffusion time is very small compared to the recuperator cycle time (e.g., 10^{-2} seconds vs. a cycle time of 5 to 10 seconds). Accordingly, the individual particulates will have essentially uniform temperatures throughout, and all portions of the particle will contribute to thermal storage during the heating and cooling phases.

Table 2.16 lists illustrative performance parameters for a rotating bed recuperat r. The parameters appear very attractive, and the system weight is quite acceptable.

The rotating bed recuperator is a relatively simple device with minimum structural requirements. All important structural components are close to the radiator temperature, with only the small diameter particulates and valves exposed to high temperatures and temperature savings. If necessary, the valves can be actively cooled since they comprise only a small area of the system.

The rotating bed recuperator has potentially high payoffs for those power systems with high working fluid temperatures, since it will considerably increase cycle efficiency as well as substantially reduce the specific mass, kg per KW(e), of the system.

Table 2.16

Illustrative Performance Parameters
For A Rotating Bed Recuperator

Power Cycle Output	1 MW(e)
Thermal Duty on Recuperator	1.5 MW(th)
Bed Cycle Time	20 seconds
Temperature Swing in Recuperator Bed During Half Cycle	100 °K
Rotating Bed Particulate Mass (2 beds)	150 kg
Bed L/D	1
Bed Inner Diameter	50 cm
Bed Thickness	7 cm
Bed Rotation Rate	500 RPM
Particulate Material	Graphite
Gas Pressure Range	30 atm Low 75 atm High
Temperature Difference Across Recuperator Bed	1000 °K
Maximum Gas Flow Velocity through Recuperator Bed	30 cm/sec
TOTAL RECUPERATOR SYSTEM WEIGHT	300 kg

2.2.7.3 Novel Energy Conversion Concepts

Novel energy conversion concepts combining direct photon conversion to electricity with thermal and chemical conversion processes have been proposed which may have the potential for performance improvements. These are reviewed below along with a new concept for direct conversion of nuclear gamma ray decay to electricity. The general thrust of these concepts is to use a portion of photon energy not participating in direct conversion as heat to assist the conversion and, thereby, improve the efficiency. In practice, this often involves degrading the temperature at which waste heat can be rejected, leading to a counter-acting effect in terms of total system weight. A thermally assisted electrolysis concept is proposed which also relies on cascaded energy use.

PHOTOELECTRIC POWER CONVERSION

Novel photon energy conversion concepts specifically include photo-assisted electrolysis, photodiodes (i.e., microrectenna), and thermophotovoltaic (TPV) cell systems. Photo-assisted electrolysis uses photons to help boost electrons over the barrier potential between a solid electrode and the electrolyte, and thereby establishes a voltage above that obtainable from the materials themselves. The photodiode is a device which rectifies electromagnetic waves in a physical antenna structure having dimensions on the order of the incident light wavelengths. The output is DC power with a voltage on the order of the light quanta energy. Discussion of the photodiode (i.e., microrectenna) is deferred to Section 2.4.7.2 (on laser power transmission) where these devices show considerable promise as receiver/converters. Thermophotovoltaic systems use a cavity heated by sunlight to 1800 ^{o}K to 2400 ^{o}K. The blackbody radiation in the cavity is absorbed by the photocells which, ideally, are transparent to all of the radiation except for the photons with energies greater than the bandgap energy, which are absorbed to make electricity. Light transmitted through or emitted by the photocells is "recycled" by the blackbody walls, which reconstitute a complete spectrum when the energy is re-emitted back at the photocells. Each of these devices is still very much in the

development stage, where efforts are being made to demonstrate the high efficiencies projected for this operation.

THERMO-PHOTOVOLTAIC CONVERSION

The thermo-photovoltaic converter was originally developed for the United States Army for application as a chemically fueled, non-detectable power source which would generate minimal noise and infrared radiation. The system has been successfully developed to a conversion efficiency near 20% for use with conventional army fuels but has evidently not been produced in any quantity. For solar energy conversion relatively high efficiencies have recently been calculated for these systems.[122] However, this high performance depends critically on the achievement of near ideal values for a number of performance parameters, particularly surface properties. Therefore, it is doubtful that the predicted high performance values can be approached. Nonetheless, some development work on these systems is in progress, and the outcome will have to be awaited before further statements can be made.

PHOTO-ASSISTED ELECTROLYSIS

Terrestrial application of solar assisted electrolysis of water (i.e., generation of hydrogen and oxygen from water) is under active investigation[123] The maximum thermodynamic efficiency, η_m, for the conversion of solar radiation into useful chemical or electrical energy is

$$\eta_m = \left[1 - \frac{4}{3}\frac{T_r}{T_s} + \frac{1}{3}\frac{T_r^4}{T_s^4}\right]$$

where the sun's temperature is approximately 5900 °K and T_r is the heat rejection temperature. More stringent restrictions are placed on η by the threshold photon energy required to make the desired reaction proceed and by the fact that concentrated sunlight is not sufficiently intense for multi-photon excitation to occur before back reactions in the photo-excited materials take place. Therefore, the fraction of energy available in sunlight is drastically reduced from the ideal limits given by η_m. These considerations generally limit the threshold-related efficiency, η_{th}, to

less than 48% for materials with maximum absorbance near 1100 nm wavelength. Assuming radiative temperatures near to 600 °K, giving η_m = 87%, the product overall efficiency is less than .87 x .48 = 42%. In practice, most photochemical reactions will have thresholds at wavelengths considerably less than the optimum for sunlight (i.e., 1100 nm) so that the efficiency will be limited to values more like 15 to 20%; a quantum yield less than 1 will reduce this value still further.

Photo-assisted electrolysis or photogalvanic systems operate by using passive electrodes immersed in a fluid solution of optically active compounds which release their chemical energy when the electrode(s) are illuminated. An electrostatic potential is also formed at the same time, allowing work to be extracted from the system. The chemical species are sometimes evolved as bubbles, which can be separated (e.g., centrifugally) from the solution in space where normal buoyant forces are inoperative. A terrestrial system is shown schematically in Figure 2.38 where bubbles rise under the gravitational buoyant forces. Typical materials used in this type of cell include iron-thiazine. The best reported efficiencies for absorbed, monochromatic light is 1.5%; broad band radiation would be substantially less efficient.[123]

Other combinations include the cis-trans acid cell, the cyclic silver halide cell, the absorbed dye layer cell, micellar systems, and bilayer membrane cells.[123] None of the cells is efficient. At this point they produce, at best, milliamperes of current making them unattractive for power applications; they may be considered for recharging batteries. Generally, however, photovoltaic cells will still perform this function best.

The liquid junction photovoltaic cell is perhaps the most attractive new idea in this area. In this concept. for example, a semiconductor such as TiO_2 is connected to a platinum counter-electrode in water, and can produce enough voltage, when exposed to short wavelength light, to dissociate water.[123] A schematic of this approach is shown in Figure 2.39. This requires the application of a bias voltage. Hence, the principle product is chemical (i.e., H_2 and O_2) and not electricity.

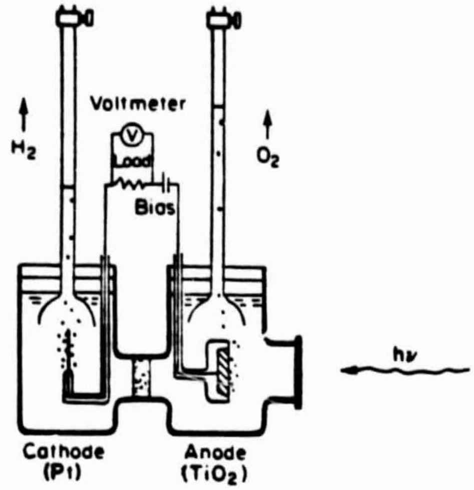


Figure 2.38. Schematic Illustration of a Classical Photo-electrolysis Cell. (Reference 123)

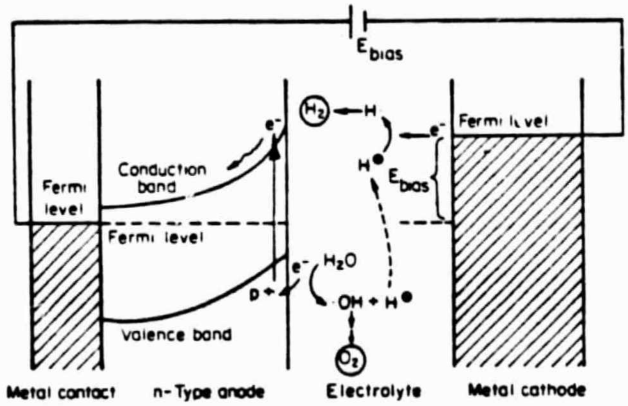


Figure 2.39. Schematic Energy-level Diagram for a Schottky-type Photoelectrolysis Cell. (Reference 123)

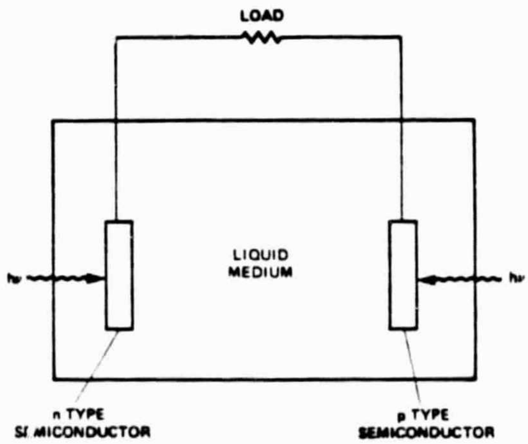


Figure 2.40. Representative Example of a Photochemical Redox Cell. (Reference 124)

Nevertheless, such fuels may be attractive when stored for pulse power or transient power (e.g., occultation) applications; for example, for use in a hydrogen oxygen fuel cell.

Other semiconductors considered for this application include GaP and semiconductor materials (p-type and n-type) which can be slurried in the electrolyte and dissociate water with no external electrical circuit (i.e., the so-called photochemical diode). This is a very active field at present, with much on-going research in the area of new classes of electrode materials.

The photo redox cell involves illumination of both electrodes (e.g., Cadmium Telluride doped n and doped p, respectively) causing charge separation and the generation of electric current through the external circuit (load), as shown in Figure 2.40. On the order of 9% solar-to-electric efficiencies have been reported with ultimate limits of 20 to 40% computed theoretically for this type of cell.(124) The weight of such devices must include the liquid and encapsulation in addition to the electrodes and wiring. Further, the question of electrode and electrolyte lifetime is uncertain and needs to be investigated before the true performance potential of this approach can be assessed.

PHOTO-EMISSIVE CONVERTERS

Gilbreath and Billman have reviewed novel direct conversion devices, including the photo-emissive converter.(124) Despite an early history of poor performance (i.e., 0.01% efficiency), these devices (see the schematic shown in Figure 2.41) can make use of relatively new, stable photo-emitter materials, such as Cs/Cs_2O monolayer on $GaAs_xP_y$ which have quantum yields of 50%, together with new device configurations. Projected efficiencies of 35% for very thin (5μ micro-etched) receivers suggest possible high payoffs, but there is very little actual data to support these figures.

Table 2.17 contains a summary of efficiency and specific mass estimates made by Gilbreath and Billman for a variety of novel energy conversion concepts.(124) Our estimates coincide very closely with those in

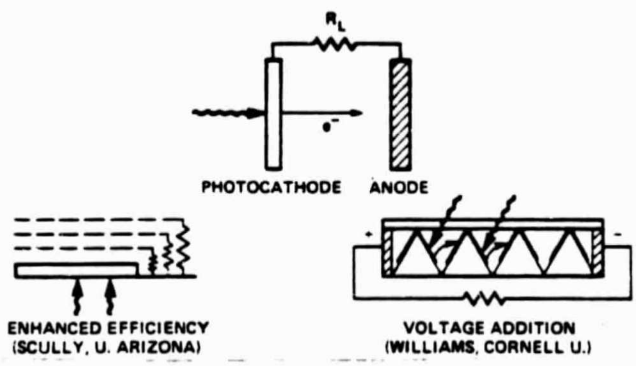


Figure 2.41. Schematic of Photoemissive Converter Concept and two examples of devices predicted to provide enhanced power conversion efficiencies and improved operating characteristics. (Reference 124)

Table 2.17

Summary Characteristics of Primary Collection and Conversion Devices
(Adapted from Reference 124)

Device	Efficiency, % solar to electric	Specific mass kg/kW_e	Power* Level
Photovoltaic	12-20	2-3	-
Redox cells	10-20	2-6	L
Photoemissive	15-30	1.2-4	L
Solar Brayton	18-25	2-3.5	M-H
Solar boiler MHD	30	2	H
Plasma collector	~1	5-30	M-H
Solar electrostatic	18-25	1.8-3	-
Thermionic	8-20	2-5	-
Dielectric conversion	5-20	2-6	-

* L: ⩽ 50 kW(e); M: 50 kW(e) ⩽, ⩽ 1 MW(e); H: 1MW(e) ⩽
A dash indicates no restriction to a particular power range

Table 2.17. We have added the additional column on applicable power range where such restrictions apply.

THERMAL-ELECTROCHEMICAL CONVERSION (TECC)

A non-mechanical, high efficiency power conversion cycle can be devised which involves two electrochemical cells operating at different temperatures. The input to the two cell system is a pure thermal one, and the output is a net electrical generation (though there is internal recirculation of electricity).

The two cells comprise a high temperature electrolyzer (HTE) and a fuel cell. In the HTE cell, the working fluid is electrolyzed using combined thermal and electrical input. The electrolysis products are then recombined in a lower temperature fuel cell, generating more voltage output than required to operate the HTE cell. The excess electricity from the fuel cell is then available for external loads. Figure 2.42 illustrates the overall cycle.

The TECC has no moving parts (except for small gas circulators which can be in parallel) and will have very high reliability since the cells can operate as modules in parallel. Stresses on components are low, and creep failure (particularly in zero G operation) does not appear to be of concern. There is extensive technical background on the electrochemical cells that would be used in a TECC cycle.

As shown in Figure 2.42 (steam TECC cycle), good net cycle efficiencies can be expected. The cycle efficiency of ~50% corresponds to a fuel cell component efficiency of 75%, which is relatively high but probably feasible. Assuming that cell over-voltage in both cells is small, the net efficiency of the TECC approaches that of the Carnot cycle based on the operating temperatures of the two cells.

H_2O (steam) and CO_2 are two promising candidate process fluids for the TECC cycle. In both cases the enthalpy of formations is essentially constant with temperature, while the ratio of thermal input ($T\Delta S$) to

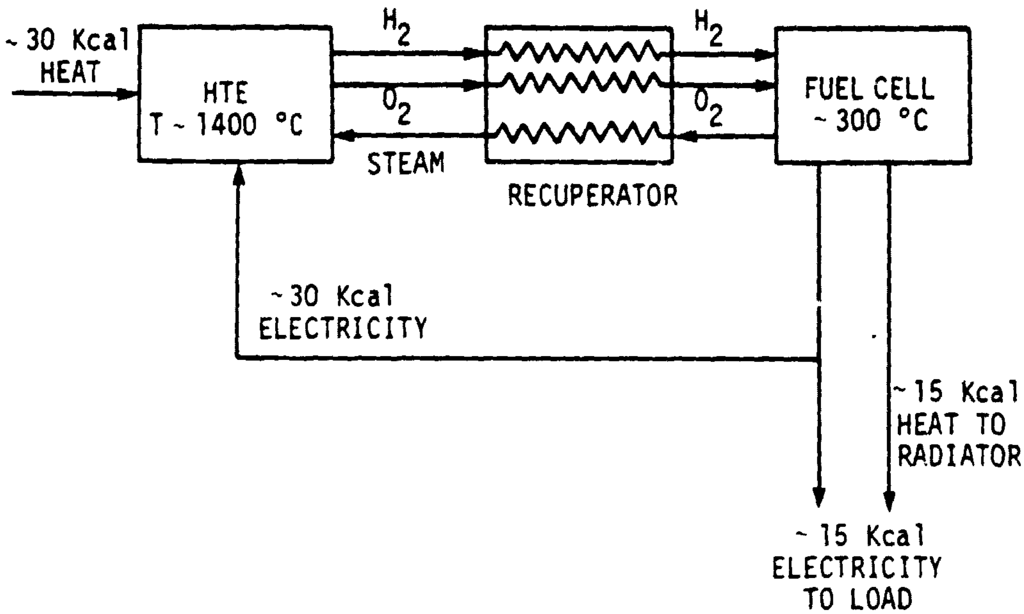


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Figure 2.42. Thermal-Electrochemical Converter Flowsheet.

electrical input (ΔG) into the HTE cell that decomposes the process fluid rapidly increases with operating temperature.

High temperatures are required if one is to operate with a high fraction of thermal input into the electrolysis cell, so that a high net cycle efficiency can be achieved. Electrolysis of steam, for example, requires a temperature of ~1500 °C if the thermal input is to equal the electrical input. CO_2 electrolysis requires similarly high temperatures.

Thin film, solid oxide HTE cells have been developed to operate at very high temperatures. These cells have thin (tens of microns thick) oxide electrodes deposited as porous refractory oxide substrates (e.g., ZrO_2 tubes). Figure 2.43 shows an HTE cell developed by Westinghouse for fuel cell applications. [Although this cell was originally developed for fuel cell applications, it also functions as an HTE cell by simply putting in electrical energy instead of taking it out.]

The reactant (either steam or CO_2) diffuses through the porous tube wall and is electrolyzed at the electrode surface to H_2 (or CO) and $O^=$ ions, which move across the electrolyte. The $O^=$ ions combine at the oxygen electrode layer to form O_2 gas.

O_2 gas is collected from the space between the HTE tubes, while the H_2 (or CO) gas product flows from inside the tubes to a collecting plenum.

The individual cells along the HTE tube are electrically connected in series by an interconnection layer so as to minimize I^2R losses in the thin electrode layers.

Single and small stacks of HTE cells have operated satisfactorily for several thousands of hours at ~1000 °C in units constructed by Westinghouse and Brown-Boveri. Large arrays have not yet been tested, but there seem to be no fundamental problems in constructing and testing such arrays.

In compatibility tests of various candidate electrode materials at temperatures above 1000 °C, Brookhaven National Laboratory has identified promising materials that appear suitable for higher temperature operation

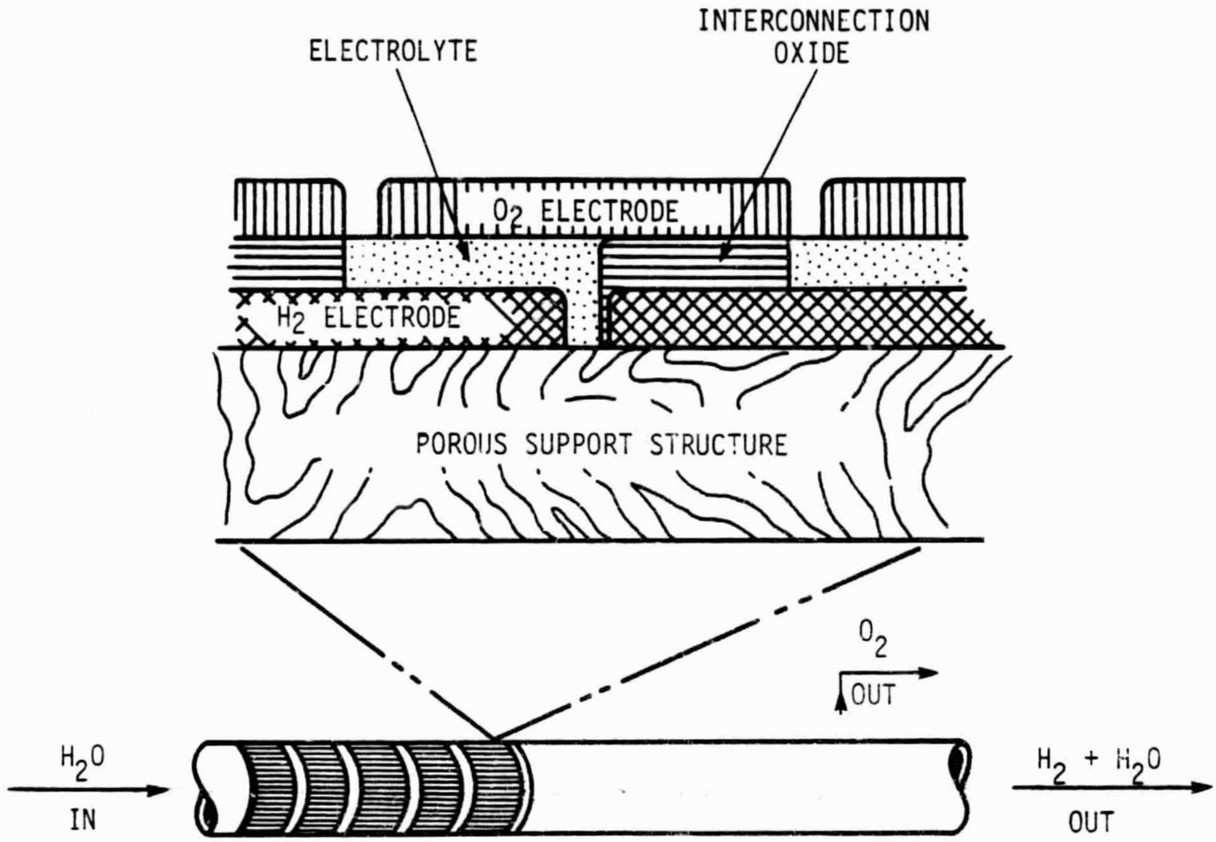

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Figure 2.43. HTE Cell Design (Westinghouse Fuel Cell).

up to ~1500 °C.[125] There are plans to construct and test cells at these temperatures, but this has not yet been done.

Candidate construction materials have been tested at Brookhaven National Laboratory for weight loss in flowing CO_2, steam, and steam-H_2 mixtures at temperatures up to ~1500 °C. Yttria-stabilized ZrO_2 has no discernable weight loss at this temperature. It thus appears to be a suitable material for HTE process units.

No detailed studies of the TEC system have been carried out, but approximate performance levels can be estimated. Overall net cycle efficiencies in the range of 40 to 50% (heat to net electrical output) appear feasible. The HTE unit would have a power density of ~3 KW(e) per m^2 of HTE electrode area (~10 MW(e) per m^3 of HTE vessel volume) and a specific mass in the range of ~1 to 2 Kg/KW(e). The specific mass of the complete energy conversion system (including fuel cell) would be several kg/KW(e).

The TEC cycle appears to be an interesting and promising energy conversion system for space power applications because of its potentially high efficiency, modularity, high reliability, and lack of moving parts.

2.2.8 Energy Conversion Conclusions

Photovoltaic cells (solar) and thermoelectric converters (nuclear) represent the state of the art for flight-tested energy conversion systems. Substantial improvements in these two conversion technologies, as well as other alternate and advanced conversion concepts, are needed in the thrust to longer lived, higher power systems. These latter concepts include Brayton and Rankine cycle systems using high temperature expanders such as advanced turbines, free piston expanders, energy exchangers and MHD generators, thermionic converters, and hybrid converters using both photons, thermal energy, and/or electricity in various combinations. The energy conversion benchmarks have been set by assuming an evolutionary advance in silicon photovoltaic technology and SiGe thermoelectric

technology in the near future leading to estimated efficiencies and power-specific masses of 16%, 10 g/We and 8%, 40 g/We, respectively.

Advanced energy conversion technologies were reviewed and their potential for better performance was assessed. Those concepts promising to perform as well or better than the benchmarks are listed in Table 2.18. Those ideas which have been selected here represent our best judgement of potential at this time. In several cases, the performance estimates are based on extremely limited data. The first order of business in any investigation should be to obtain a more precise estimate; in some cases this is just a matter of collecting data which already exists, and in other cases the critical data must be generated. In most of the entries of Table 2.18, the entire energy conversion system weight (e.g., including solar collectors and radiators) is accounted for by the power-specific mass. The exceptions are the last two items in Table 2.18, which do not include radiator weights. Concepts which were not identified for Table 2.18 may be worth development either as part of current programs where they are already being supported (e.g., advanced turbine blade materials) or in the event that any gains for improvement perceived for them in the future would not be significantly greater than the benchmarks. A periodic reassessment of such concepts is necessary to keep track of recent changes in the development of these technologies and to reconsider them for the Advanced Energetics Program.

In addition, we also recommend a series of studies to help generate additional data needed for evaluating advanced conversion technologies and for determining their relative merits. These are:

- Evaluate relative advantages of concentrator photovoltaics versus flat photovoltaic arrays

- Evaluate the relative advantages of solar thermal versus photovoltaic power systems

Table 2.18

Most Promising Advanced Energy Conversion Concepts

Device/Concept	Specific Mass [g/W(e)]	Efficiency* (%)
Photovoltaics:		
High Concentration Cells (GaAs)	5	18
Radiation Resistance and Annealing	NA	NA
Higher Voltage Arrays (VMJ)	10	16
Improved Single Cell Performance	NA	18-20
Multi-Band Gap Cells	3	30-40
Thermoelectric:		
High Temperature Thermoelectric Materials	40	8
Particle-Filled TEC/TE Converter	NA†	20
AMTEC (and Thermogalvenic) Concepts	33	25
Thermionic:		
High Temperature Insulating Materials and/or Concepts	20	20
Cascaded TEC/TE Converter	20	19
Thermal Dynamic:		
Free Piston Expander	8	30
Energy Exchanger	8	40-50
MHD Generator	7	40
High Temperature Recuperator	–¶	--∏
Hybrid Concepts		
Thermophotovoltaics	10	30-40
Photoemissive Converters	4 δ	35
Thermo Electrochemical Conversion	5 δ	40-50

* Efficiency = Electrical Power Out ÷ Energy Received

† Data is not available in quantifiable form

∏ Dash indicates the entry is not applicable

¶ Measured in g/W(th)

δ Does not include radiator mass

- Review and evaluate alternate high temperature gas expanders for thermal power systems

- Compare the relative merits of thermophotovoltaic, thermionic, and thermoelectric power systems.

2.3 Energy Storage

2.3.1 Introduction

Energy storage for secondary power systems may be considered to comprise all energy storage systems excluding those for propulsion. In today's technology this function is performed by batteries, which are electrochemical devices. For future applications we can consider four additional generic approaches to energy storage: regenerable fuel cells, flywheels, thermal and chemical, and novel. Batteries and regenerable fuel cells receive and deliver electrical energy, storing the energy chemically. Using motor-generator auxiliary equipment, flywheels also can receive and deliver electrical energy, storing the energy dynamically. The catch-all "novel" approach is applied to hybrid approaches, new concepts, and approaches that reduce or eliminate the need for energy storage.

Energy storage technology is closely interrelated with energy conversion technology. If one sets up a matrix with the various forms of energy input listed along the left column and the various forms of energy output listed along the top row, the various storage technologies will be found along the diagonal of this diagram (Table 2.19). Quite often it is advantageous to combine a pure storage system with an energy conversion system. These types of technologies can be found in the fields adjacent to the diagonal. Some of these combined storage/conversion schemes have not yet been fully developed and offer potential improvements for future advanced energetics developments.

All energy storage systems, which so far have been used on Earth only, should be scrutinized with regard to their ability to operate in a zero-g environment. Gravitational environments related to the Earth's would be encountered for planetary surface missions. The most common

Table 2.19

Energy Input and Output Technologies*

ENERGY INPUT FORM \ ENERGY OUTPUT FORM	ELECTRICITY	HEAT ΔH	CHEMICALS (e.g., H_2)	PHOTONS $h\nu$	MECHANICAL $\frac{1}{2}\theta\omega^2$
ELECTRICITY	STORAGE BATTERIES REVERSIBLE FUEL CELLS SUPERCONDUCTING MAGNETS CAPACITORS FLYWHEEL w/MOTOR GENERATOR	RESISTANCE HEATERS MECHANICAL HEAT PUMPS	ELECTROLYSIS	LIGHT BULBS GAS DISCHARGE TUBES LEDs LASERS	ELECTROMAGNETIC MOTORS
HEAT ΔH	THERMOELECTRIC GENERATORS THERMIONIC GENERATORS THERMALLY REGENERATIVE FUEL CELLS	SENSIBLE HEAT STORAGE PHASE CHANGE MATERIAL REVERSIBLE CHEMICAL REACTIONS	THERMOCHEMICAL WATER SPLITTING CYCLES	BLACKBODY RADIATORS	HEAT ENGINES
CHEMICALS (e.g., H_2)	FUEL CELLS	COMBUSTORS	METAL HYDRIDES	CHEMICAL LASERS	GAS TURBINES
PHOTONS $h\nu$	PHOTOVOLTAIC	BLACKBODY CAVITY ABSORBERS PHOTOLYSIS via RCR	PHOTOLYSIS PHOTOELECTROLYSIS	PHOSPHORESCENCE	RADIOMETER
MECHANICAL $\frac{1}{2}\theta\omega^2$	ELECTROMAGNETIC/ELECTROSTATIC GENERATORS FLYWHEEL w/GENERATOR	FRICTION	UNDEVELOPED	TRIBOLUMINESCENCE	FLYWHEELS

*Storage technologies are along the diagonal.

mission envelope would typically be a spacecraft or manned permanent space station with zero g in Earth orbit with a period of revolution varying from approximately 100 minutes to 24 hours (in geosynchronous orbit). Depending on the inclination and eccentricity of the orbit, the spacecraft may spend from four percent to a little less than half of its time in the shadow of the Earth. Energy storage of some sort is required to keep the systems on board operating during sun occultation.

2.3.2 Requirements

Future NASA spacecraft mission categories to be considered for energy storage technology research are:

- Low Earth Orbit satellites (LEO)
- Geosynchronous Orbit satellites (GEO)
- Near sun missions
- Planetary orbit missions
- Energy conversion for space propulsion
- Space-to-space power transmission
- Deep space missions
- Lunar surface

Finke and Barthelemy(126) identify an important future need for 20 kW to 50 kW synchronous orbit power systems with ten year life. They proposed a typical requirement for a 25 kW system with a peak power need of approximately 50 kW and a battery storage capacity of approximately 2.5 kW·hr. These requirements reflect NASA and Air Force synchronous orbit expectations, giving recognition to civilian and DOD expected needs. Thus, this requirement is accepted as a valid one.

For GEO synchronous orbit missions, there are approximately 84 discharges per year, with needs presumed to be on the order of ten years. Special emphasis is warranted to the GEO synchronous orbit missions because launch weight is especially critical. Finke and Barthelemy have established a tentative technology goal for energy storage for this mission

of 123 W-hr/kg (60 W-hr/lb). When compared with the current usable secondary battery energy density on the order of 23.1 W-hr/kg (10.5 W-hr/lb) it is seen that refinements of existing systems will not be adequate, but that totally different approaches will be necessary. An assessment of technology under current development, as discussed in a later section, shows that this goal is very ambitious.

Requirements for Low Earth Orbit (LEO) missions have not been defined as clearly as for GEO synchronous orbit missions but are understood to extend beyond 20 kW to 50 kW and even to 100 kW. Unfortunately, the energy storage requirements for low Earth orbit missions are somewhat uncertain. It has been presumed, therefore, that (a) weight is important, though not so much as for GEO synchronous orbits; (b) life is important; and (c) cost is important.

For low Earth orbit missions there are approximately 15 discharges per day, with approximately 1.0 hour for charge and 0.6 hour for discharge. It is presumed that such costly, high power spacecraft will require long life, in excess of five years. Further definition of requirements for low Earth orbit missions, similar to that done by Finke and Barthelemy[126] for GEO synchronous orbit missions, would be of benefit in research planning. Improved energy density is undoubtably of value, although specific goals cannot be cited.

Non-Earth orbital missions require non-cyclic energy storage such as from a primary battery. Energy density should be very high because of the great importance of weight for such missions.

Stored thermal or chemical energy usually must be converted to electrical energy for use in spacecraft. For comparison with other systems, it has been assumed that the conversion efficiency from thermal or chemical energy in a thermal cycle to electrical energy is 20 percent.

2.3.3 Energy Storage Methods

Energy storage methods that may be considered for space applications are batteries, regenerable fuel cells, flywheels, thermal or chemical, and novel. These are briefly described below.

2.3.3.1 Batteries

Batteries store energy chemically, transforming it into electrical energy upon discharge. Primary batteries are discharged only once and cannot be recharged; such batteries have applicability to many NASA missions beyond Earth. Secondary batteries may be discharged and recharged many cycles; these batteries are used for Earth orbital and some planetary orbital missions.

2.3.3.2 Regenerable Fuel Cells

A fuel cell is similar to a battery except that the reactants, either liquids or gases, are stored externally and plumbed into the cell. A regenerable fuel cell system is reversible, having a recharge cycle in which the discharge product is electrochemically converted to the initial reactant state. Hydrogen-oxygen and hydrogen-halogen regenerable fuel cells are candidates for future spacecraft.

2.3.3.3 Flywheels

Flywheels release and absorb kinetic energy by changes in rotational speed. This energy can be converted to electrical energy by a generator with either dc or non-constant frequency ac output. Related technologies include homopolar generators and compulsators.

2.3.3.4 Thermal and Chemical

Thermal energy storage is the storage of energy as heat without changing the form of energy. Chemical energy storage, on the other hand, includes thermochemical, photochemical, and radiochemical storage. Thermochemical energy storage is based on the heat which accompanies

chemical reactions. Reversible reactions are required for cycling of energy. The thermal energy can be used directly for temperature control or may be converted to electrical or mechanical forms by heat engines, thermoelectric, thermoionic, or other means.

2.3.3.5 Novel Energy Storage Approaches

Very little effort has gone into conceiving and analyzing novel approaches to energy storage for space applications. The concepts mentioned here are merely by way of illustration to point out that there is much room for innovation. There appear to be good possibilities for novel high energy density storage approaches for GEO synchronous orbit applications due to the limited cycle life requirement, the low charge rate requirement, and the availability of long durations for rehabilitation prior to the next occultation season. Some examples follow.

1. Reclamation of Secondary Batteries: Lithium batteries (as well as some others) have very high energy density but poor cycle life. One cause of the poor cycle life is that the lithium reacts at a slow but finite rate with the electrolyte, forming electrochemically irreversible byproducts. Conceivably, special treatment could periodically be given these reaction byproducts to rejuvenate the degraded active materials.

2. The electrical power system can be configured with two sets of batteries: one of medium energy density but of long cycle life to be used for housekeeping loads, and the other of high energy density but uncertain with regard to long cycle life and to be used for payloads.

3. For synchronous orbit, batteries could be practically eliminated by use of ground based lasers transmitting during occultation. Solar panels are Earth facing at

this time, and transmission would be in wavelengths useful to solar cells. Multiple transmitters could circumvent problems of clouds.

4. Flywheel energy storage could be integrated with the control moment gyros of the attitude control system for possible weight saving.

5. Thermochemical energy storage might prove useful in temperature control applications as well as in conversion to electric energy. This can be more weight efficient than the use of electric heaters, and can minimize thermal cycling of thermoelectric and thermoionic converters.

6. Thermoelectrochemical engines such as the Li/I_2 can be considered. These consist of pairs of electrically coupled electrochemical cells operating at different temperatures, and usually involve a gas phase energy storage medium which also takes part in an electrode reaction. Such systems are new and have never been studied for spacecraft application.

2.3.4 General Limits to Present Technology

The nickel-cadmium battery system has a theoretical energy density of 220.5 W-hr/kg (100 W-hr/lb).[127] Considerable experience has been obtained with this system. The highest energy density achieved in a cell is 55.1 W-hr/kg (25 W-hr/lb),[128] but rate and cycle life with such designs are not adequate for spacecraft use. Typical aerospace batteries of lightweight construction use cells which will deliver approximately 31 W-hr/kg (14 W-hr/lb). Modest improvements in cells to approximately 35 W-hr/kg (15.9 W-hr/lb) are possible and can be reflected in batteries for an energy density of approximately 32 W-hr/kg (14.5 W-hr/lb).

The nickel-hydrogen system has a theoretical energy density of 443 W-hr/kg (200.7 W-hr/lb).[129] This is a recently developed system, but the technology has advanced rapidly because the nickel electrode is well developed from the nickel-cadmium battery, and the hydrogen electrode is well developed from hydrogen-oxygen fuel cell technology. Single cells currently have an energy density of approximately 47 W-hr/kg (21.3 W-hr/lb), resulting in batteries with an energy density of 33 W-hr/kg (15 W-hr/lb).[130] Weight saving improvements are possible in the nickel electrodes, the cell container, and in the battery packaging. It is judged that a battery energy density of 50 W-hr/kg (22.7 W-hr/lb)is attainable in this system for LEO, and 60 to 75 W-hr/kg (27.2 to 34.0 W-hr/lb) for GEO.

High temperature alkali metal batteries such as Li/FeS and Na/S are presently under development. Li/FeS batteries have attained an energy density of 80 W-hr/kg (36.3 W-hr/lb) and Na/S batteries are expected to provide from 70 to 110 W-hr/kg (31.7 to 49.9 W-hr/lb). Both systems have life and performance problems, so it is expected that energy density of fully developed systems will not exceed these values.

The status of other energy storage technologies is included in the technical assessments of Section 2.3.7 since none of the other technologies have been developed yet for flight testing.

2.3.5 Basis of Comparison

Secondary batteries are the state of the art energy storage method, and are used as the basis of comparison. Most of the flight experience has been obtained with nickel cadmium batteries, which have an energy density for full discharge of approximately 28.7 W-hr/kg (13 W-hrs/lb). Typical depth of discharge (DOD) for near Earth orbit is 25 percent, for a usable energy density of 7.17 W-hr/kg (3.25 W-hr/lb).

Nickel hydrogen batteries currently have an energy density for full discharge of approximately 33.1 W-hr/kg (15 W-hrs/lb). With today's technology, these could be designed for 40 W-hr/kg for GEO and 33 W-hr/kg for LEO. Though there is little flight experience so far with this new

system, cell and battery designs are well advanced. Typical design DOD for LEO is estimated to be 40 percent and 70 percent for GEO, resulting in usable energy densities of 13.2 W-hr/kg and 24.5 W-hr/kg, respectively.

Though the nickel hydrogen battery system is relatively new, it is in the advanced stages of development, having been used on some programs and committed for others. Therefore, the nickel hydrogen battery has been selected as the basis of comparison. The usable energy density per cycle is taken to be the appropriate measure of performance. Thus, the reference points are 13.2 W-hr/kg for LEO, and 24.5 W-hr/kg for GEO.

2.3.6 Applicability to Generic Missions

Future mission categories are listed in Table 2.20, with the applicability of the several energy storage methods indicated. It is seen that the three general methods of energy storage are applicable to low Earth orbit and geosynchronous orbit satellites, with relatively little or no application to the other missions. These two missions also appear to be of great importance in the NASA space program. It should also be noted that high energy density primary batteries are important for many missions, and that thermochemical energy storage has potential for application to the lunar surface mission as well as near-Earth and geosynchronous orbit missions.

2.3.7 Advanced Energy Storage Technology Assessments

Advanced and new battery technologies as well as terrestial energy storage technologies including regenerable fuel cells, flywheels, thermal and thermochemical storage and novel energy storage approaches are assessed. The state of the art of these technologies is reviewed and estimates made for their potential to surpass the benchmark for energy storage set in Section 2.3.5 by the nickel hydrogen battery. Specific concepts are identified where possible, and these have been compared in order to recommend the most attractive ideas for research in Section 2.3.8.

Table 2.20

Applicability of Energy Storage to Space Power Missions

Mission	Comment	Energy Storage Applicability		
		Flywheels	Thermo-Chemical[1]	Electro-Chemical
Near Earth Satellites	Cost is important; weight is moderately important; life is important.	Yes	Yes	Yes
Geosynchronous Satellites	Weight is very important; life is very important.	Yes	Minor	Yes
Near Sun Missions	Energy storage need is minor.	Minor	Minor	Minor[3]
Planetary Orbit Missions	Possible storage for peak power during data transmission; possible need for solar based power systems.	Minor	Minor	Minor[3]
Energy Conversion for Space Propulsion	No energy storage need.	No	Yes	No
Space-to-Space Power Transmission	Energy storage need probably only slight.	Minor	Minor	Minor
Deep Space Mission	Energy storage for peak transmission.	Minor	Minor	Minor[3]
Lunar Surface	Two weeks storage if solar based power	No	Yes[2]	Minor[3]

[1]Usable with thermal converter power system.

[2]Usable for temperature control.

[3]High energy density primary batteries required.

2.3.7.1 Battery Assessment

Silver-Zinc and Nickel-Zinc Batteries: Some well established aerospace battery systems have so little potential for high energy density and long life that they may be disqualified at the outset from further consideration. The silver-zinc and the nickel-zinc systems have high energy density, but suffer from poor low cycle life. The cycle life limitation is due to the high solubility of zinc species, and is thus an inherent restriction on these systems. Unless some bold new, promising approach can be taken, such as operating in electrolytes with low zinc solubility or with solid ionic-conducting electrolytes, these systems cannot be recommended for research.

Recommendations with regard to silver-zinc and nickel-zinc batteries are as follows:

> Silver-zinc and nickel zinc systems with alkaline electrolyte cannot be recommended for research. However, novel approaches may be entertained for obtaining long cycle life and high energy density with these systems.

Nickel Cadmium Batteries: Nickel cadmium batteries have been the workhorse of space power batteries since the inception of the space program. Nickel hydrogen batteries are superior with respect to life and weight performance, though admittedly this has not been fully verified by long-term cycling data. Nickel cadmium batteries have a cost advantage over nickel hydrogen, and there are many missions that are well within the capability of nickel cadmium batteries. Thus, we may expect a continuing need to use nickel cadmium batteries, to understand their problems and weaknesses, and to try to improve the technology.

Research to improve nickel cadmium batteries would not be enabling and cannot be justified by the need for high energy density batteries. It can be justified, however, on its continued importance to the space

program. This is especially valid in light of the fact that nickel cadmium batteries share with traveling wave tube amplifiers the distinction of being the most troublesome components in spacecraft. Research on the nickel electrode would be especially valuable for it would benefit both the nickel cadmium system and the nickel hydrogen system.

Research efforts in batteries tend to emphasize the development of batteries; research on ways to control battery manufacturing so that a reliable, repeatable product can be made is mostly neglected. One important lesson learned from nickel cadmium technology is the great importance of understanding the effects of manufacturing variables and developing ways to keep them under close control. This lesson must be applied to any new battery system developed for spacecraft use.

Recommended research on nickel-cadmium batteries is summarized as follows:

(1) Research, at a modest level, should be conducted on nickel cadmium batteries to better understand their problems and weaknesses and to improve the technology.

(2) Research should be conducted on the nickel electrode to benefit both nickel cadmium and nickel hydrogen battery technologies.

Nickel-Hydrogen Batteries: Nickel hydrogen batteries have been selected as the basis of comparison for all energy systems, as discussed in Section 2.3.5. This is a consequence of the system's good cycle life, even though there is little flight experience with this system, as well as the somewhat improved energy density relative to nickel cadmium batteries. The nickel hydrogen system is an extremely unusual battery system because, except for minor traces, neither electrode involves the formation of soluble species. The biggest problem with cycle life of practically all batteries is the changes in electrodes which occur when active materials go into solution and then precipitate in a different morphology. This

fundamental problem is avoided in the nickel hydrogen system and, as a result, the system has the potential for unusually long cycle life and very deep depths of discharge. Other inherent attributes are also desirable, such as ability to tolerate reversal and excellent high rate capability. Without question, this system will be very important for many years.

NASA should exploit the long life prepotency of the nickel hydrogen system by conducting research on life limiting processes. Such research is worthwhile, irrespective of energy density improvement objectives, for reliable, long life battery operation in itself is a major goal in NASA research.

Research on the nickel-hydrogen system is even further justified by the large improvement in energy density that is possible. Weight improvement can be accomplished both by engineering measures and electrochemical advances. Engineering measures include: (1) lighter containers than steel, such as titanium, fiberglass composites, or carbon fiber composites; (2) development of a bi-cell, consisting of two cells in series with a common pressure vessel; (3) optimization of battery packaging for heat removal, incorporating heat pipes into the design if necessary, and even developing ways to couple battery heat pipes with spacecraft radiator heat pipes.

Electrochemical measures include: (1) development of lightweight nickel electrodes, preferably with properties intermediate between plastic bonded and sintered construction; (2) research to approach a two-electron transfer (already demonstrated experimentally) instead of only one electron transfer.

Research to improve the nickel electrode has high leverage in performance for the nickel electrode is a high fraction of the weight of nickel-hydrogen cells. It should be emphasized that, although millions of dollars have been spent to date on nickel-hydrogen battery research, an overwhelmingly large fraction of this has been on engineering of the system with relatively little effort on basic research to understand problems and

overcome the impediments to improving the systems, especially the nickel electrode. Future research must place greater emphasis on basic research.

In assessing nickel hydrogen technology today and the prospects for the future, it is concluded that this system is without peer for LEO missions, whereas for GEO missions it is a strong competitor but not the ultimate (Table 2.21). For LEO missions, an energy density of 33 W-hr/kg at full discharge is attainable with today's technology, resulting in a usable energy density of 13.2 W-hr/kg at 40 percent depth of discharge. For GEO missions, an energy density of 40 W-hr/kg is attainable with today's technology, resulting in a usable energy density of 24.5 W-hr/kg at 70 percent depth of discharge.

With research to improve nickel-hydrogen batteries, significant improvements are possible. For LEO missions, an energy density of 50 W-hr/kg at full discharge should be attainable, resulting in a usable energy density of 30 W-hr/kg at 60 percent depth of discharge. For GEO missions, an energy density of 60 to 75 W-hr/kg at full discharge should be attainable, resulting in a usable energy density of 48 to 60 Whr/kg at 80 percent depth of discharge. It should be emphasized that these projections are based on complete batteries, not just the cells.

Recommended research in nickel hydrogen battery technology is summarized as follows:

(1) An analysis should be made showing energy density obtainable by R & D. Such an analysis would need to be made in considerably more detail than has been possible in this study.

(2) A nickel electrode research program should be undertaken. This should include a comprehensive review of the nickel electrode.

Table 2.21

Battery Performance Benchmarks and
Performance Judged Attainable With R & D

		Benchmarks	Attainable With R & D	
	Battery Type	Nickel-Hydrogen	High Temperature Alkali Metal	Advanced Nickel Hydrogen
Geosynchronous Orbit (GEO)	Energy Density at 100% DOD	33 W-hr/kg (15 W-hr/lb)	70 W-hr/kg (31.7 W-hr/lb)	60 W-hr/kg (27.2 W-hr/lb)
	Design DOD	70%	70%	80%
	Usable Energy Density	23.1 W-hr/kg (10.5 W-hr/lb)	49 W-hr/kg (22.2 W-hr/lb)	48 W-hr/kg (21.8 W-hr/lb)
	Battery Type	Nickel-Hydrogen	Advanced Nickel Hydrogen	
Low Earth Orbit (LEO)	Energy Density at 100% DOD	33 W-hr/kg (15 W-hr/lb)	50 W-hr/kg (22.7 W-hr/lb)	
	Design DOD	40%	60%	
	Usable Energy Density	13.2 W-hr/kg (6.0 W-hr/lb)	30 W-hr/kg (13.6 W-hr/lb)	

[1] Not flight proven, but judged to be state of the art.

(3) A nickel-hydrogen technology program should be undertaken.

Silver-Hydrogen Batteries: Silver-hydrogen batteries have potential for efficient energy storage for GEO applications. Energy density is greater than that of nickel-hydrogen batteries, but designing for long life is a greater problem. There is a difficult electrolyte management problem, but there is no inherent reason why this cannot be solved. It has been thought that there is a silver migration problem, which would limit system life; however, recent studies of this show that silver does not migrate significantly.

NASA has had a research program on this system, but it has been discontinued. Research on this system has been underway in Europe for a number of years. One experiment with silver-hydrogen cells resulted in 1500 cycles at 75 percent depth of discharge. Cause of failure was corrosion of the substrate, a problem that should be readily solvable.

For GEO missions, silver-hydrogen batteries should attain an energy density of 70 to 90 W-hr/kg with full discharge. With design to a maximum depth of discharge of 70 percent, a usable energy density of 49 to 63 W-hr/kg should be attainable. This system is, therefore, recommended for further research, and that research should not be terminated unless it can be demonstrated that there is an inherent process operating in this system which limits cycle life below required levels.

Recommended research in silver-hydrogen batteries is summarized as follows: A silver-hydrogen cell research program should be undertaken, and the research results obtained in Europe should be closely monitored.

High Temperature Batteries: High temperature batteries are attractive possibilities for energy storage because they offer both high power density and high energy density. High energy density is achieved by selecting reactants of low equivalent weight (such as lithium, sodium, sulfur) and high electronegativity difference. High power capability is attained by use of low resistance electrolyte materials, such as molten

salts, and by operating at elevated temperature, which increases the rates of reactions and transport processes, resulting in a high exchange current density; high temperature also makes possible the achievement of a high degree of reversibility.

High temperature batteries may loosely be divided into three groups: (1) those with a molten salt as the sole electrolyte, such as the system LiAl/LiCl-KCl/FeS, (2) those with a combination of a solid main electrolyte, and a molten salt mix of reactant and subsidiary electrolyte, such as the system $Na/Na^{+}glass/S-Na_2S_n$, and (3) solid state batteries in which both electrodes and electrolyte are solids, such as the system $Ca/CaF_2 + YF_3/NiF_2$.

Paradoxically, the best known, highly funded high temperature battery programs have unimpressive prospects for application to future spacecraft. One reason is that the systems picked for development were selected based on totally different criteria than are needed for space. Thus, potentially low cost has been paramount for commercial applications, whereas of lesser importance for aerospace; long cycle life with high reliability is pre-eminent for aerospace, whereas commercial needs are less demanding. Thus, high temperature battery development for aerospace applications must consider many approaches that could not be entertained for commercial applications.

Development of high temperature batteries is a non-trivial undertaking. It would be inappropriate to attempt to identify the one most deserving system that should be given research emphasis; a separate study to do this is, in fact, one of the recommendations of this section. Many of the candidate systems are identified below, however. An energy density of 70 to 90 W-hr/kg should be attainable at full discharge for geosynchronous orbit missions. With design to a maximum depth of discharge of 70 percent, a usable energy density of 49 to 63 W-hr/kg should be attainable. In making these energy density projections, the following process was used:

1. Projections were made based on application of high temperature alkaline metal batteries now under development, with allowance for aerospace design needs and rate requirements.

2. Theoretical energy density of several other candidate battery systems not under development was found to be equally high, suggesting that similar useful energy densities might be obtained if the R & D problems were solved.

Candidate High Temperature Batteries include:

1. Li-Al/FeS_1. Argonne National Laboratory is developing this system.[131] Operating temperature is 450-475 ^oC, using a LiCl-KCl molten electrolyte. Hundreds of cells have been tested, but progress has been slow. On the order of $5 million has been spent on this system, providing a reference point to the cost of technology for high temperature batteries. Many basic technical problems remain with this system. Indications are that this is not an inherently long life system. Ability to discharge efficiently at the rates needed for GEO is also a problem, and the relative capacity at typical S/C rates is low (see Figure 2.44).

2. Li_4Si/FeS_2. Rockwell[132] and GM[133] have done the most work on this system. Operating temperature is 450-475 ^oC, using a LiCl-KCl molten electrolyte. Work is at an early stage, but results so far are somewhat encouraging. One of the major problems is capacity fading of the upper voltage plateau. Ability to discharge efficiently at the rates needed for GEO is also a problem.

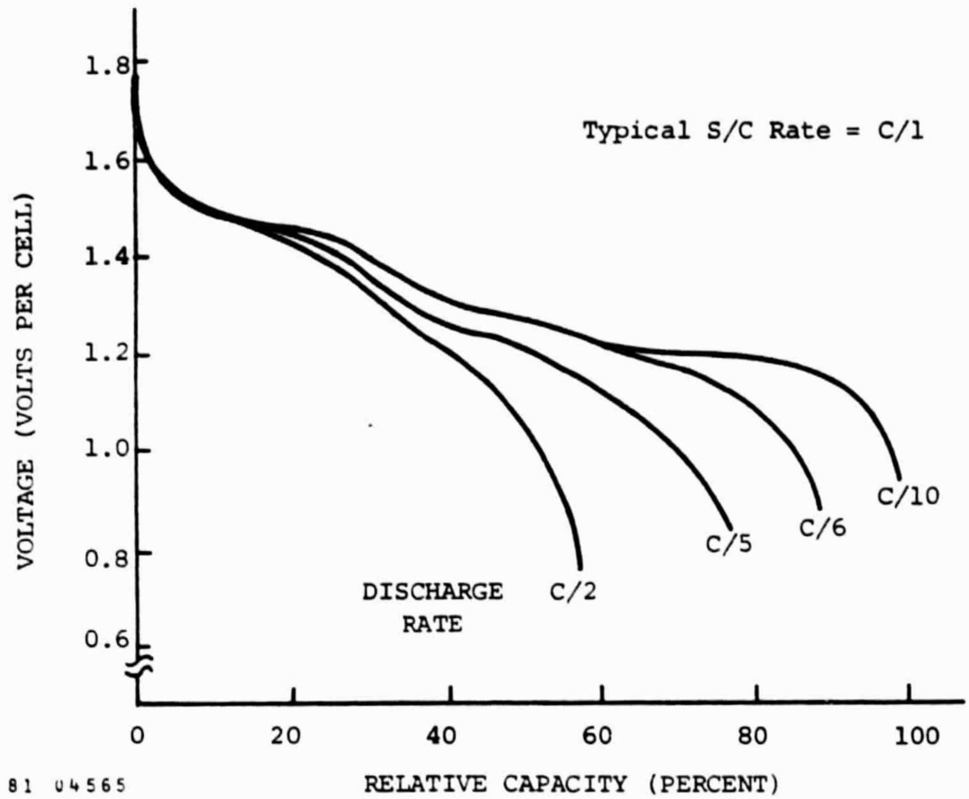

Figure 2.44. Typical Discharge Voltage for a $LiAl/FeS_2$ Battery.

3. Ca_2Si/FeS_2. Argonne Labs is working on this system, which is in an early stage of development.[134] The molten electrolyte is a four-part mixture of LiCl-NaCl-$CaCl_2$-$BaCl_2$. Though work with this system is just beginning, it has been found that high solubility sulfur species are not formed in the electrochemical reactions at the positive electrode, so long lifetimes may be possible.

4. Na/S. Large programs have been underway all over the world on sodium sulfur batteries.[135] Beta-alumina (or its derivatives) is used as the solid, ionically conductive ceramic separator. Both sulfur and sodium are in the liquid state. Marginal durability of the ceramic separator is a major problem with this system. Ability to discharge efficiently at the rates needed for GEO is also a problem (Figure 2.45).

5. Na/SCl_3AlCl_4. This system is a recent entry into high temperature batteries.[136] An advantage is the unusually high voltage (4.2 V). The relatively low operating temperature of 255 ^oC is an advantage for commercial applications, but may be a disadvantage for aerospace use because of the low conductivity of the beta-alumina separator at such temperatures. The system's good reversibility, over 400 cycles so far, compels that this system be given serious consideration, however.

6. $Na/SbCl_3$. This cell is referred to variously as the sodium chloride cell (NaCl is part of the discharge product) or the antimony trichloride cell. This system operates at the especially low temperature, for molten salt systems, of 200 ^oC, where corrosion containment

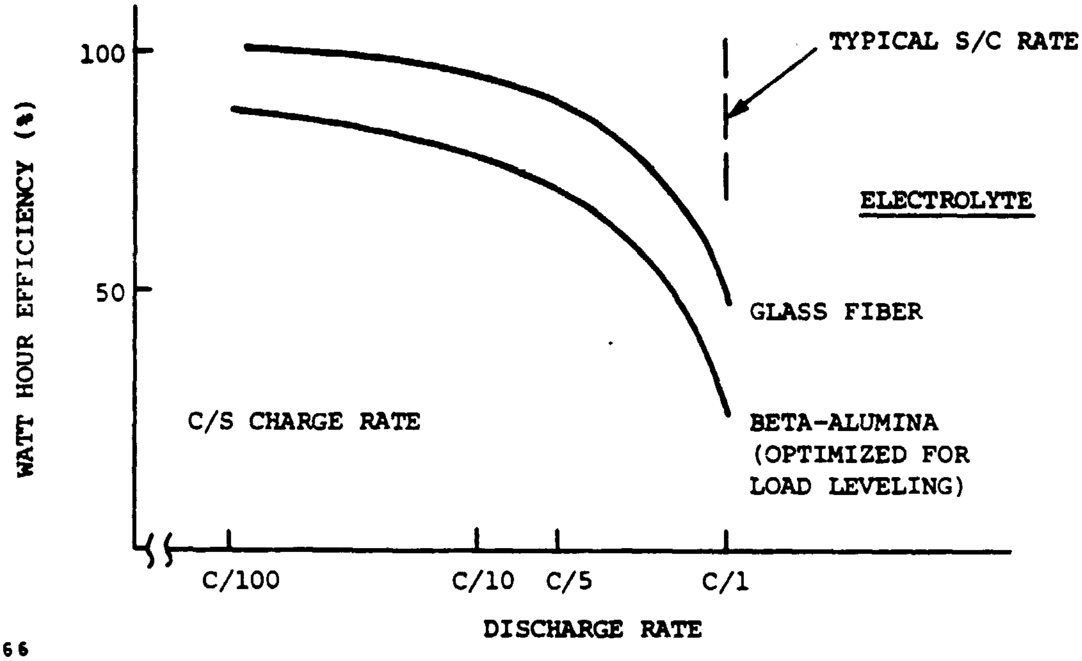

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Figure 2.45. Sodium-Sulfur Battery Efficiency.

and seal problems are relatively mild. The low conductivity of beta-alumina electrolyte at this temperature is a disadvantage. There is some promise of good cycle life with this system, however.

7. $Li/TeCl_4$. High cost of materials has contributed to lack of commercial interest in this system, which operates at 400 °C. Good cycle life justifies its appraisal for aerospace use.

8. Na/Se. To the knowledge of this writer, no experimental work has been done on this system. Selenium and sulfur are in the same family, and much work on sodium/sulfur batteries should be directly transferable. A higher power density should be attainable with selenium than with sulfur.

9. K/S. The theoretical energy density of this system is nearly the same as the sodium/sulfur system. If a solid electrolyte can be developed which is a good conductor of potassium ions, then this system could be worthwhile.

10. Li/Se. High energy density and high power density should be possible with this system. High cost and limited availability of materials may not be a major problem for space use.

11. Li/Te. The short supply of tellurium has discouraged commercial development of this promising system. Otherwise, the system has good prospects and should be evaluated for aerospace use.

12. Be/NiF. High energy density and reversibility of this system suggest it for consideration for aerospace use. The molten salt electrolyte is a mixture of fluoride salts; operation is at about 450 °C.

13. Be/AgF_2. High energy density and reversibility suggest consideration of this system for aerospace use. The molten salt electrolyte is a mixture of fluoride salts; operation is at about 450 °C.

14. Ca/NiF_2. This is an all solid state battery system, using doped CaF_2 as the electrolyte. Operation is at about 450 °C. Improvements in conductivity are needed. The fact that the system is all solid state is of great interest from a life and reliability standpoint.

Recommended research on high temperature batteries is summarized as follows:

(1) A study should be made of all candidate high temperature battery systems to determine realistic energy densities to be expected and to determine those systems best deserving of research. This should include couples currently not under development.

(2) NASA should develop expertise in high temperature batteries and establish a long-range program.

(3) NASA should establish a program on super-ionic solid state conductors for use in development of high temperature batteries.

Battery-Related Topics: Research in battery systems should not only include the energy storage devices, but should also include items related to the entire system. Two such items to be mentioned briefly in this regard are autonomous operation and reliability.

There are a variety of reasons why power systems should limit their dependence upon ground control for their well being. These include lack of continuous contact with the ground, ground system outages, high cost of ground crew surveillance, and need at times for fast response. It is necessary, therefore, to develop systems which monitor state of health of batteries and use this information in automatic on-board control of the batteries and, in fact, all components in the electrical power system. This will require the development of new tools for monitoring and determining the state of health of batteries and will require also that battery systems be configured in ways that failures and problems can be compensated for and the effects of failures minimized.

Reliability considerations dictate that failure of some battery cells should not necessarily result in failure of the entire battery. To design battery systems so they will degrade gradually rather than fail in relatively large increments, it is necessary to do a considerable amount of switching. This is inordinately heavy with components available today and requires the development of lightweight switching. Multikilowatt spacecraft will have dozens of batteries, chargers, regulators, and other power components, and the problem of switching becomes formidable. Solid state switches, which are a close equivalent to relays, are needed. Such developments would greatly improve reliability and life, for failed battery cells or modules can more easily be switched out.

Two important devices which are keys to this development are (1) the inverted transistor, which has a voltage drop less than 0.1 V, but, unfortunately, has too low a breakdown voltage (less than 9 V); and (2) V-MOS power FET's, which have high breakdown voltage (35 to 90 V) and low leakage current when off (0.5 micro-ampere) but too high a resistance when on (about 1.4 ohm at 1.0 ampere). Research to improve these two devices is

needed, with the aim of using them for lightweight switching (see Section 2.5).

Recommended research on battery-related topics is summarized as follows:

(1) Develop methods for monitoring batteries and determining their state-of-health.

(2) Develop ways to use battery state-of-health information and apply it to the development of autonomous operation of battery systems.

(3) Develop lightweight switching for reconfiguring cells, battery modules, chargers, or other components when failures occur.

Ambient Temperature Lithium Batteries: Much effort has been directed nationally to the development of high energy density secondary lithium batteries. NASA also has a good sized program on this. Intercalation systems predominate in all research programs with major emphasis given to the following systems: Li/TiS_2; Li/MoS_2; Li/V_6O_{13}; and $Li/CuCO_2S_4$.

Maximum cycle life is about 150 to 200 cycles. There are apparent limitations on cycle life due primarily to reaction of lithium with the electrolyte. There are research directions that could be taken to cope with this problem, but these are not being pursued in the NASA program. An equally serious limitation is on the reaction rates of ambient temperature lithium batteries - they cannot be discharged anywhere near the rates required to support spacecraft during eclipse periods.

It is concluded that ambient temperature lithium secondary batteries are not appropriate for NASA's main needs. It is recommended that the

current NASA program on this subject be redirected to avenues more likely to meet the NASA future energy storage needs.

Recommendations in ambient temperature lithium batteries are summarized as follows:

> The current NASA research program on ambient temperature lithium secondary batteries is not appropriate to NASA's main needs, so this work should not be continued.

Primary Batteries: Many high energy density primary battery systems are available today, especially for low rate discharge. In addition to military funding of such work, much privately funded research and development is occurring in the industry because of the commercial economic importance of such systems. Primary batteries have a number of NASA applications, but these appear not to be mission enabling. As such, large research activities in this areas cannot be justified.

In spite of all the activity in high energy density batteries, few of these new systems are qualified for space nor have they all been investigated more than superficially for reliability and safety. Also, insufficient data is available on these new systems. Comprehensive safety and performance verification is needed for lithium batteries in manned applications, such as the shuttle.

One important problem is the need for a method to determine the state-of-charge of lithium primary cells without discharging them. It is useful to know whether a battery planned for flight is fully charged, as expected. A promising approach for assessing state-of-charge is the use of special pulse discharges, carefully controlled and analyzed.

Another need is the development of small aerospace quality lithium primary cells for electronics memory retention, an application that will be much used in the future. Mass produced commercial cells are presently considered unsuitable for aerospace applications. Although there are other

ways to provide backup electric power to microprocessors, the primary cell can provide independent power that cannot be interrupted and which does not require additional power processing and distribution.

Recommended research on primary batteries is summarized as follows:

1. Research on safety should be conducted on those lithium battery systems currently planned for NASA manned missions, such as the shuttle.

2. Research should be performed to develop a non-destructive state-of-charge test for lithium primary cells.

3. Aerospace quality primary lithium cells should be developed for electronics memory retention applications.

Battery Assessment Summary: Based on technology available today, nickel hydrogen batteries are the best approaches for both GEO and LEO missions and are used as the basis of comparison. Performance attainable with today's technology is summarized in Table 2.21. Improved nickel hydrogen batteries offer the best promise for future LEO missions. High temperature batteries and silver-hydrogen batteries offer the best promise for future GEO missions, although the prospects for advanced nickel-hydrogen batteries are also quite good. Performance of these systems judged attainable with research is also summarized in Table 2.21.

Silver-zinc and nickel-zinc batteries show insufficient promise to warrant research. Nickel cadmium batteries will continue to be important to the space program. Although their improvement would not be enabling, continuation of research on them is worthwhile. Research on nickel-hydrogen batteries is especially worthwhile, particularly on the nickel

electrode. Silver-hydrogen batteries should also be researched, at least until definitive answers can be given on prospects for this system.

2.3.7.2 Regenerable Fuel Cells Assessment

Due to the high energy density of the reactants hydrogen and oxygen, the development of light weight hydrogen-oxygen fuel cells has been made possible. The reactants are stored externally as either liquids or gases and plumbed into the fuel cell. Practically all fuel cell applications to date have been as primary systems; that is, reacting to generate electricity and the product water.

Regenerable fuel cells not only generate electricity but also reverse the process, converting the discharge product electrochemically to the initial reactant state through the consumption of electrical energy. Emphasis on regenerable fuel cells has been with the hydrogen-oxygen system, though the hydrogen-bromine system and the hydrogen-chlorine system are also candidates. The regeneration can take place either in a separate unit, usually called the electrolyzer, or in the fuel cell using bifunctional electrodes.

In spite of all past studies, it is still uncertain whether the regenerable fuel cell is advantageous over batteries for future high power applications. A complexity of factors must be skillfully considered in such an evaluation, and this has not yet been done. Weight alone is not a sufficient criterion. It should be noted that prior studies have been directed at LEO rather than GEO, which has the more important energy storage problems. Therefore, it is recommended that information generated in past studies be reviewed, supplemented as necessary by additional information, and an evaluation made. Recommendations should be made to either continue the present NASA program, modify it by concentrating on critical items, or to abandon this effort. The following factors must be considered in this evaluation:

1. Sufficient redundancy and automatic control must be included in the fuel cell system to make the overall reliability high - comparable to batteries - and provide a reasonable degree of autonomy.

2. Batteries used for comparison should not be those available today but those advanced batteries which could with reasonable confidence be developed in the same time period.

3. Suitable means must be used to evaluate the impact due to the fuel cell requiring greater development and unit cost, more frequent resupply, and greater required solar panel area as compared with batteries.

4. Valid results must be established for GEO, recognizing that prior studies have been directed at LEO.

5. An assessment of the hydrogen-bromine regenerable fuel cell system should be included because of its higher energy and potentially longer lifetime.

Recommendations with regard to regenerable fuel cells are summarized as follows:

(1) A review should be made of all past studies on regenerable fuel cells, and comparisons made against advanced batteries.

(2) Valid results must be established for GEO.

(3) Recommendations should be made whether or not to continue the NASA regenerable fuel cell program.

2.3.7.3 Flywheels

Flywheels are a generic class of energy storage devices where the energy storage is proportional to $I\omega^2$, where I is the moment of inertia and ω is the angular velocity. Energy extraction can be achieved most easily as electrical power. Several technologies have evolved for extraction, including conventional generators, homopolar generators, and compulsators, in order of decreasing extraction time. The rotor and support technologies are reviewed below, followed by a brief discussion of several promising extraction techniques.

ROTOR

For any given system parameters, flywheel system energy density is roughly proportional to that of the rotor. The energy per unit weight which can be stored in a flywheel rotor is directly proportional to the allowable stress-to-density ratio obtainable in the material. For an isotropic constant strength material, such as some metals, the mathematical solution to a constant-stress optimized wheel derived by Stodola in 1924 still represents the state of the art.[137] This gives a wheel a thick hub with an exponentially thinning rim, which is truncated in various ways for a practical design. However, real materials are not uniform in allowable stress because their properties vary with thickness due to the hardening and forming processes used. Therefore, a better optimum could be realized by including this dependence in the mathematical optimization of the shape. However, there is little reason to believe this optimum will significantly improve on the present designs (8 W-hr/lb obtained with titanium Stodola wheels). One such wheel system with mechanical bearings was developed by Rockwell and delivered to NASA-Langley Research Center.[138]

Composite filament wound materials are anisotropic; their properties (strength, stiffness, etc.) vary with orientation. Tensile strength is very high in the direction of fiber length, but the normal strength and shear strength are quite small. Therefore, it is possible to create thin hoop-shaped structures by filament or tape winding processes which have

primarily circumferential strength. Thin hoops have been built and tested which demonstrated 80 to 90 W-hr/lb using Kevlar. However, attemps to make the hoop radially thicker produce radial stresses in the weak direction, and failure occurs at lower energy densities. This is often aggravated by locked-in thermal radial stresses due to processing problems.

The result is that disc or hollow cylinder designs tend to break radially if a significant fraction of the circumferential design strength is used. Simple solid, circumferentially wound discs of Kevlar composite actually have not achieved as good an energy density as isotropic metal wheels. S-glass, which has somewhat better transverse characteristics due to a more developed method of bonding fiber to matrix, does somewhat better but is still not impressive for solid discs. Goodyear Aerospace is now working on improved matrix characteristics for Kevlar wheels.[139] Rockwell has done rather well with graphite-epoxy composites.[140]

One approach to solving this problem is to put an outer radial fiber wrap of Kevlar on the rotor after the circumferential inner hub is cured. This adds some radial strength and helps carry the radial loads on the inner matrix material. At present, it is not clear that the outer wrap does not create more problems than it solves by introducing discontinuities in the radial properties.

A second approach being tried is to build up a radially thick structure out of thin hoops which are discontinuous and thus strain-relieved at their interfaces. By using a number of concentric thin hoops in a bicycle-wheel shaped assembly with flexible spokes, Garret-AiResearch Corporation has achieved an impressive 31 W-hr/lb performance on a number of Kevlar rotors storing from tens of W-hrs. to several kilowatt hours.[141] The precise method of bonding concentric rings together at Garrett is proprietary but involves preloading fiber tension and ring interference fits held together by friction. However, these structures were test devices and need to be evaluated for flight criteria. A variation of this approach using concentric rings of different properties tied together with elastomers has been plagued with dynamics problems. Dynamics problems broke the wheel-hub bond in one Garrett wheel.

A third approach is to weave the fibers in the rotor in different directions so as to give the structure strength in the radial and axial directions as well as the circumferential. This requires a three-dimensional "polar weave" capability which General Electric's RESD facility and others have developed for nose cones. GE has produced several Kevlar rotors of this design and expects to achieve 50 W-hr/lb with them, but has not yet tested them beyond the 5 W-hr/lb level.(142)

A fourth variation, used by AVCO and developed to about the same point over a longer period of time, builds up a radially thick flywheel by using a two-dimensional weave to get circumferential and radial strength and then laminates these together axially.(143)

All four of these approaches are currently under test and should show 20 to 40 W-hr/lb performance if design expectations are achieved.

The most promising current experiments with anisotropic rotor design are being done at Johns Hopkins Applied Physics Laboratory.(144) Using bare filament Kevlar and other materials, rotors are wound without glue on a metal hub. Spokes of the same material are wrapped through the hub, around the periphery, and then glued to give some radial and axial strength to the wheel. The resulting rotor is attached to a thin shaft with a metal and rubber shock mount to allow self-centering. Results have reached 30 to 40 W-hr/lb in this solid disc configuration, in spite of problems in bonding spokes to circumferentials. Due to the lack of glue on the circumferentials, the potential hoop strength is nearly double other designs.

In summary, the composite rotor represents a technical risk but appears well worthwhile as a weight-saving advantage and an advance in the state of the art for energy storage.

The information presented at the 1980 Flywheel Technology Symposium showed that flywheel designs are numerous and varied.(145) Composite rotors are typically achieving energy densities of 20 to 30 W-hr/lb. Future developments should double the energy density of these units before

materials limitations become dominant. Testing to date is summarized in Figure 2.46.

Based on this data, it appears that rotor development is proceeding in a satisfactory manner and that rotors will soon be available which are:

1. Reasonably light (40 to 60 W-hr/lb);

2. Self-pulverizing (no high energy penetrating fragments at failure).

Flywheel systems can be assumed from previous studies to weigh twice the rotor weight, including electronics and supports.

MAGNETIC BEARINGS

The magnetic bearing represents a significant improvement in the long-term reliability and lifetime expectancy of high speed spinning assemblies. A combination of permanent magnets and electromagnets is used to levitate a rotor between the poles of the magnetic bearing. The resulting structure has no contacting surfaces to require lubrication. The bearing is limited in force density by the magnetic saturation characteristics of iron so that size, weight, and power are dominated by the need to support the rotor in a 1 G environment. Zero-G applications are an excellent match for these bearings.

In addition, a magnetic bearing is a "soft" support in that its restoring spring constant is relatively weak compared to mechanical bearings. Therefore, such a system is characterized by clearance dimensions measured in mils or tens of mils rather than the tens of micro-inches typical of conventional ball bearings. Such soft bearings effectively isolate rotor from mounting when imbalance vibrations occur. Also, they allow a relatively crudely balanced rotor to spin about its principal axis with minimum effect on the system performance. However, the low stiffness places lim[illegible] the allowable cross-axis spin rate which causes lateral torque on [illegible]e spinning flywheel.

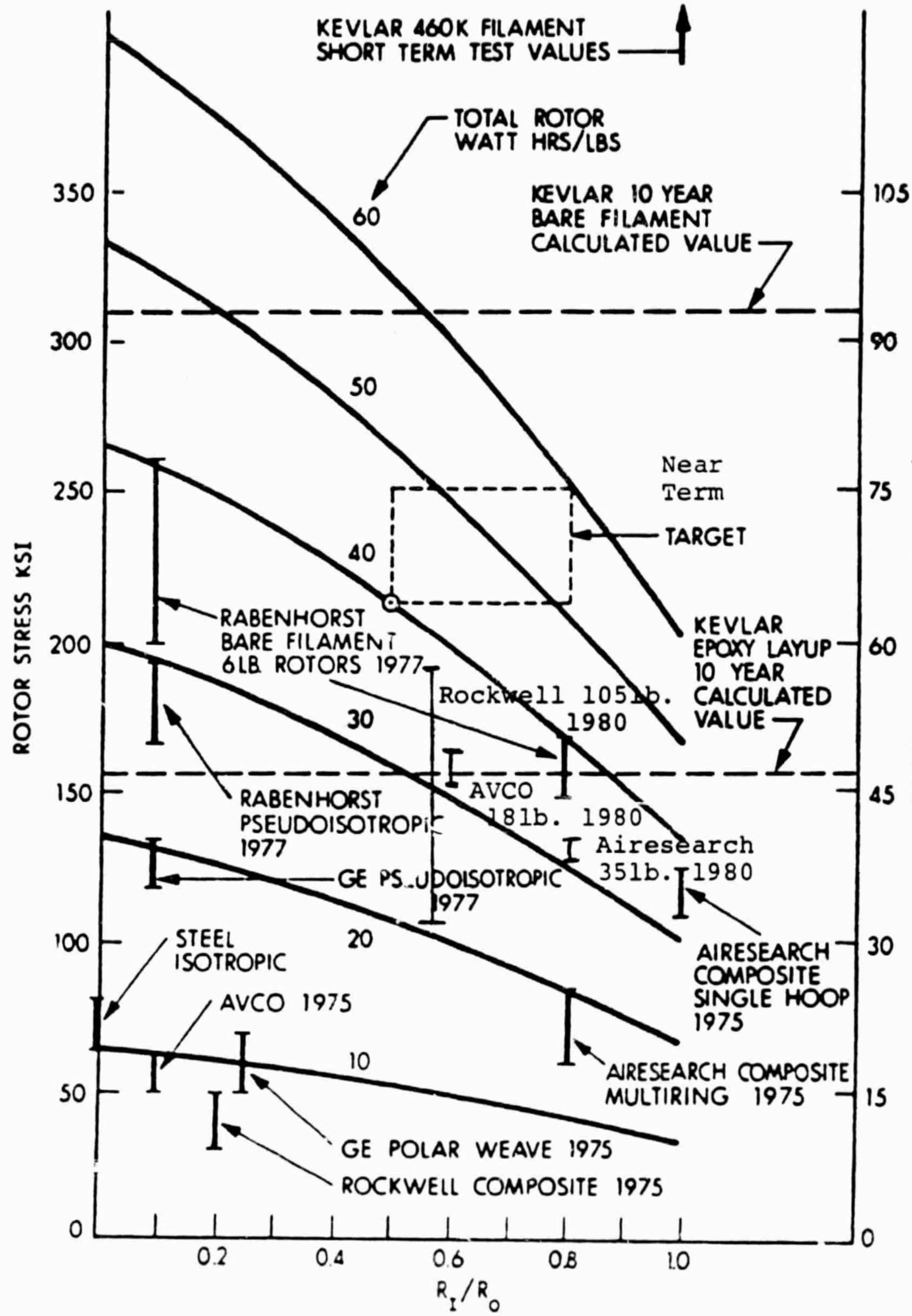

Figure 2.46. Rotor Testing - Summary of the State-Of-The-Art.

At present, several gyro and momentum wheel vendors are investing in magnetic bearing technology to apply these bearings to inertial navigational systems and large momentum wheels. Cambion Corporation, which invented the magnetic bearing and has accumulated a long record of innovations in this field, has retrofitted several wheels for Bendix in the hope of interesting some customers of Bendix systems in an experiment promising longer lifetimes and, eventually, higher speeds.[146] Sperry-Rand Corporation, Flight Systems Division, has developed a considerable in-house magnetic bearing capability and has developed these bearings for its momentum wheels to extend their lifetime.[147]

Most work at Sperry has been with radially passive, axially active permanent magnet systems for momentum wheels. Rather large steel rotors have been floated using this system.

Aerospatiale (France) has developed a permanent magnet bearing for a momentum wheel with a composite rotor.[148] This radially passive, axially active system has relatively high input power requirements, due in part to the imbalances from a composite rotor and in part from the many magnetic components in this design. It includes a passive magnetic damper for oscillations about the transverse directions. This wheel design is an ambitious use of several new technologies with a rather complex implementation. It is the most developed unit of its kind, and has been qualified for COMSAT.

Teldix (Germany) has a metal wheel with 5-axis active magnetic bearings.[149] This allows limited magnetic gimballing of the rotor by changing the set points of the transverse position loops. The limit is the maximum gimbal angle, done to small clearance in the magnetic gaps. The MDR series wheel at 100 N-M-S has a $\pm$ 1/2° gimbal capability, and has many coils for sensors, bearings, and motor which are single-point failures. However, engineering radial wheels with 1.2° gimballing and fully redundant coils have been built (not qualified) and demonstrated automatic fault correction. The MDR wheel, flight qualified for COMSAT, appears to be a very well-engineered unit, clearly implemented and easily inspected or repaired. The bandwidth of its servo loops is set by the wheel nutation

frequency, and is not too much lower than the comparable permanent magnet system due to high (16K rpm) wheel speed. Other manufacturers of high-speed rotating equipment are moving more slowly in applying these bearings.

A fundamental statement derived from Maxwell's equations, known as Earnshaw's Law, states that no static assembly of permanent magnets and ferromagnetic materials will suspend a device in stable equilibrium. This means that at least one degree of freedom of the rotor in a magnetic bearing system must be stabilized by active feedback electronics. Passively stable behavior can be obtained axially (along the spin axis) or radially (perpendicular to the spin axis) but not both. For energy storage it appears that a passive-radial, active-axial system will allow fully redundant electronics and electromagnets to be used with a simple arrangement. The radially passive containment can be achieved with permanent magnets while electromagnets at each end of the shaft are used for axial stabilization. Proper design allows either electromagnet to perform the function if one should fail. Key design parameters are low weight and realization of the potential for low power. This design represents state of the art engineering using Samarium-Cobalt permanent magnet materials in ways which do not exceed their limited stress capabilities.

The Lincoln Experimental Satellite (LES) flywheel system was conceived and designed as a component to supply storage of energy and angular momentum in an experimental communications spacecraft. A test bed system and brassboard were built and tested.[150] The brassboard bearing system was designed to support a 25-pound spacecraft rotor. It provides up to 200 pounds of lift in the vertical direction. The electrical power dissipated in the bearings is a total of one watt for a 200 pound mass. The measured drag in the brassboard bearing system, without motor-generator, was 9×10^{-6} inch-ounces per RPM. This would allow energy storage over a period of four months before 90 percent of the energy was dissipated in bearing drag.

There appear to be several limiting items in available magnetic bearing designs. The first is complexity. For situations which do not allow the power dissipation or complex circuitry of 5-axis active systems, a radially passive, axially active permanent magnet scheme looks most attractive. However, the Aerospatiale system with this end in mind was still very complex due to separate bearings for each direction and separate magnetic dampers and sensors. The Sperry bearing looks simplest, yet even it has three magnetic loops and a relatively heavy and complex magnetic pole structure. An improvement in magnetic flux topology with plenty of iron in the pole pieces to allow low drag from flux nonuniformities appears possible. The MIT/LL magnetic bearing was an attempt to achieve this improvement.(151)

Weight is another limit. Many magnetic bearing designs weigh more than the supported shaft and wheel. A great deal of weight appears often to be associated with the bearing station support to avoid beading mode coupling to the stabilization loops. By placing sensors very close to the magnetic coils and yet truly axisymmetric to avoid shaft runout signals, it is possible to drastically reduce this weight.

The third limitation is bandwidth. This is determined by the instability in position due to use of permanent magnets for power minimization. Wide bandwidth is required for a very stiff bearing with a large ratio of active-axis to passive-axis stiffness. This implies a heavy structure and interaction with other spacecraft structural elements.

Finally, the drag of a magnetic bearing is inherently determined by the nonuniformity of field and the conductance of reacting structures. The MIT/LL bearing uses geometry of the iron pole pieces to attempt to minimize the effects of magnet iron and uses no copper dampers to avoid conductance in the resulting structures.(152)

TOUCHDOWN BEARINGS

The magnetic bearings would not be designed to withstand launch vibration and shock, power failures, or accidental test handling mishaps. These loads would be absorbed by a "touchdown" or backup ball bearing which makes no contact with the rotor under operating conditions, but prevents contact of the magnetic components and complete failure in case of mishap. This bearing will require careful design to avoid brinelling or breaking during a high speed spin down. It must withstand high accelerations without significant deterioration. For large energy wheels, this bearing represents a development item which Sperry, Bendix, or Draper Laboratories can design with existing technology and is an engineering development item of relatively low risk. For smaller wheels, the present MIT/LL design is adequate.

EXTRACTION TECHNIQUES

The design of small, light, efficient motor generators is an art. The key to the most advanced designs is to use Samarium-Cobalt magnets on the rotor without exceeding the stress limits of the material and to minimize eddy current losses in the stator windings without sacrificing efficiency.

The Samarium-Cobalt permanent magnet material is relatively new and represents a new generation of capability and performance for rotating machinery. Its energy product is an order of magnitude higher than previously available materials, and its high coercive force lends itself well to an ironless armature machine which will have lower drag than other designs. Typical extraction times are on the order of 1 second to hours. For example, seventy percent cycle efficiency for a 10-hour charge, 12.8 hour coast, 1.2 hour discharge is desired for geostationary missions. Rockwell's flywheel uses a GE design and achieves adequate motor-generator performance for these conditions with a very low technical risk in this item.(138) The MIT Lincoln Lab effort with Sperry improved the solution to the problem using an axial gap ironless armature approach for lowest drag losses.(150) The MIT/Sperry design uses a special titanium support

structure to reduce stresses on the rotating magnets, combined with a structure minimizing losses and low cost fabrication techniques.

In contrast to advanced conventional generators such as those described above, the homopolar generator is designed to extract energy from a flywheel in shorter times of 1 msec to 1 sec long. Disk, spool, and drum rotor configurations are used, with the latter providing the lowest stress and lowest internal impedance characteristics. Power is taken off by brushes in mechanical contact with the rotor (completing an external load carrying circuit). Conventional or magnetic bearings can be used with disk and spool type homopolars because they are spun about a center axle. Drum rotors are usually supported by gas film bearings surrounding the periphery of the device. The Energy Storage group at the University of Texas at Austin has developed several homopolar devices; for example, operating at 0.7 sec discharge times, 560 kA pulses for a total of 5 MJ of stored energy.[153] Rotor tip speeds are typically 80 to 170 m/sec, and energy retrieval efficiencies can be as high as 90 to 95%. The energy storage density is somewhat more difficult to estimate since most of the systems have not been optimized for low weight. Estimates range from 1 to 2 kJ/kg for devices which have been built in the range of 5 MJ to 50 MJ storage.[154] Brushes are the key area requiring development for extending the lifetime and reliability of these devices.

The compensated pulsed alternator or compulsator is very similar to the homopolar generator but extracts power in very short pulses on the order of 0.1 to 1 msec. It is best suited for driving capacitive or resistive loads. Experimental compulsators have been built and tested, but a substantial amount of development is still required in order to achieve projected performance levels of efficient, low inductance, short pulse power delivery.[155] Both the University of Texas at Austin and JPL are presently conducting research in this area.

C-3

SHAFT AND HOUSING DESIGN

The shaft and housing for the flywheel system represent a significant part of the system weight. They are to provide rigid mounting support for wheel alignment, estimated to be tens of arc seconds to avoid attitude control interaction with power demands, and also provide a vacuum enclosure for ground testing. There is no doubt that these can be built. Use of composite materials for lighter weight and, perhaps, flywheel failure containment could be considered but may be a technical risk.

SUMMARY OF POTENTIAL

Flywheel energy storage represents a promising technology being actively advanced by current DOE efforts through a program managed at the Lawrence Livermore Research Laboratory. In spacecraft applications, it provides the following attractive features:

1. High energy density (low weight)

2. Independent sizing of power conversion and storage elements

3. Pulsed high power load capability

4. Integrated power and attitude control capability using antiparallel wheel pairs as diagrammed in Figure 2.47

5. Ability to function reliably in a wide range of thermal environments, allowing a relaxation of spacecraft thermal control requirements

6. Long life and high reliability

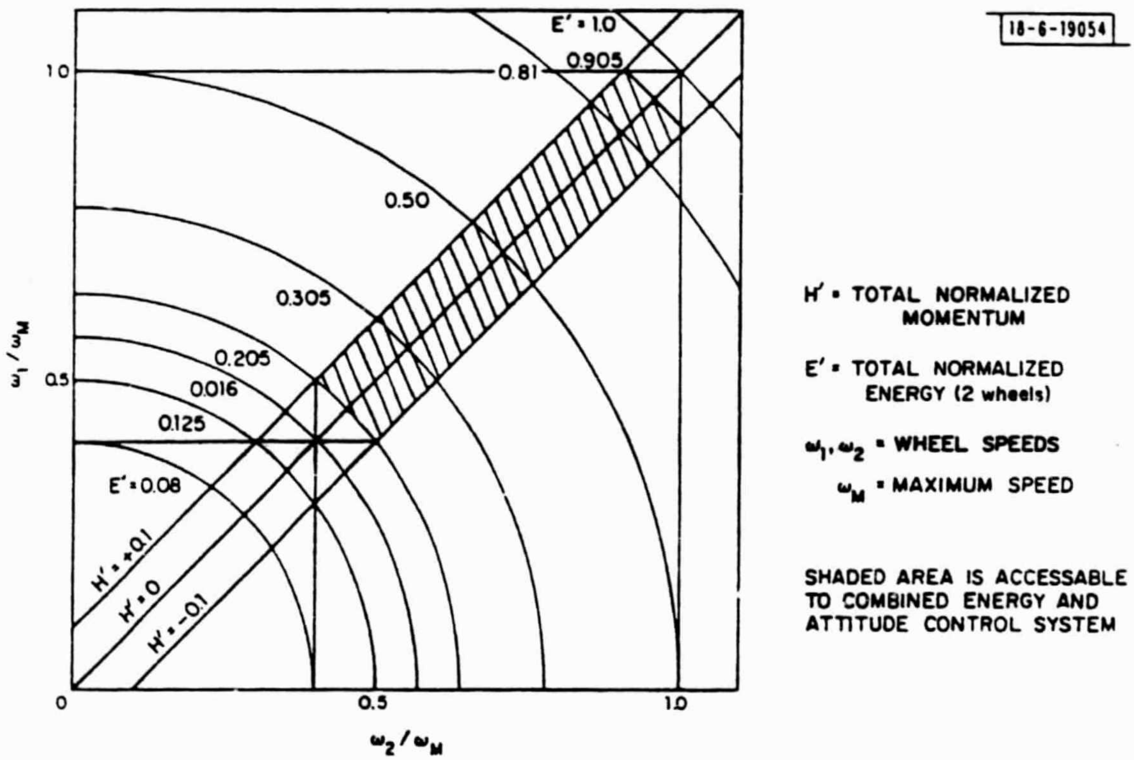

Figure 2.47. Flywheel Parameter Relationship.

Key performance parameters are best compared with state of the art NiH_2 batteries. These are done on a <u>system</u> basis including conditioning and control electronics, and supporting structures. (A flywheel system typically weighs 2 to 3 times the rotor alone).

NiH_2 batteries can provide about 6 W-hr/lb (see Section 2.3.5). This figure is tabulated below for projected flywheel systems, at 2 times rotor weight:

	Usable	Burst
In-use systems	5	10
Reliable components	10	15
R&D items	15	25
Potential	30–40	50–60

Power density is also of interest. NiH_2 batteries provide about 30 W/lb, compared with perhaps 100 W/lb for flywheel systems. Here, the power conditioning needed for the end-use is often included in the flywheel circuitry, giving extra flexibility as well as possibilities of AC distribution systems.

Self-discharge rates of 50 hours are possible with NiH_2 systems, whereas flywheels can reach lower drag levels and longer hours if the power requirements and resulting motor-generator losses are small. Lifetimes of 3 to 6 years in LEO, and 10 to 15 years in geosynchronous orbit are comparable, although flywheel lifetimes are not proven at present due to lack of magnetic bearing experiments.

2.3.7.4 Thermal/Chemical Energy Storage Technologies

THERMAL ENERGY APPLICATIONS

Most thermal energy needs on spacecraft (e.g., for preventing liquid propellants from freezing) are currently being satisfied by proper thermal management of incident solar radiation as long as the spacecraft is close enough to the sun. To a lesser extent, electric resistance heaters are used to prevent propellant freezing or to maintain temperatures of other critical components (e.g., electronics package, vidicons, sensors) within a range of normal operating temperatures. Electric power for these auxiliary heaters is usually derived from solar panels or, as in the case of VIKING Lander and VOYAGER fly-by missions, from radioisotope thermal generators (RTGs). The consideration of nuclear energy for powering Earth satellites has apparently been discontinued for civilian NASA missions. For this reason thermal and thermochemical storage may gain increased importance for solar powered near-Earth orbital missions.

Another less frequent use of thermal storage using phase change materials (PCM) is not for the purpose of power generation but for the purpose of passive thermal control. In this mode the PCM provides cooling instead of heating and prevents the overheating of delicate spacecraft components. A low-temperature PCM canister containing n-heptane and methylethylketone has already been used on operational satellites and has helped to delay an undesirable warming trend.[156,157]

Extending cooling requirements (as opposed to heating or power generation requirements) to even lower temperatures, energy storage schemes are sought which will allow the maintenance of cryogenic temperatures for infrared sensors or for superconducting magnets in space. Several of the metal hydride reversible chemical reaction systems can be used for cooling cycles.

The rapidly growing area of space processing brings with it new requirements for thermal energy in LEO Space Shuttle/Spacelab missions.[158] Potential products produced in space are large single

crystals, new metal alloys, and semiconductor materials. Raw materials could be melted by placing them directly into the focal point of a solar collector or by circulating a hot fluid which has previously been heated in a solar receiver. In order to achieve the desired uniformity of crystal structure (free from contaminants and faults or with a carefully controlled amount of dopants and lattice defects), the cooldown has to proceed very slowly and may require several Earth revolutions. Removal of heat from the process vessel by simply radiating it away would result in variable cooldown rates, depending on whether the spacecraft is in the Earth's shadow or not. Exchanging heat with a circulating molten salt coolant from a thermal storage system will allow uniform cooldown rates and will result in a more reproducible product.

Other thermal energy requirements which have so far (on comparatively short orbital missions) been satisfied with electric power are for life support and waste management systems. Up to this time there have been no attempts to regenerate oxygen and water from space cabin atmospheres or human wastes on previous space flights, although closed system simulation tests have been conducted on the ground. Sufficient water and oxygen was carried on board the spacecraft during APOLLO and SKYLAB to last for the entire mission. It will be inevitable to use CO_2 and waste regeneration on long-term missions of the future, even in LEO or GEO. Thermal energy is required for reducing CO_2 to breathing oxygen and to reprocess wastes to obtain potable water. These chemical processes operate best in a steady state mode. On-again, off-again operation when operating the system with direct solar input would result in a very inefficient system. Thermal energy storage would level the cyclic heat input and allow the CO_2/waste reprocessing system to operate at a constant load.

Up to this time solar thermal electric conversion (STEC) power plants have not been used in space, although the high intensity of incident solar radiation and the freedom from atmospheric effects (clouds, haze, dust, wind, thermal convection) would make the space environment ideal for STEC power plants. STEC technology is currently being developed for

terrestrial applications in desert climates. Some of the demonstration plants (e.g., Barstow, California) will include thermal storage as sensible heat in hot oil and hot rocks, in order to compensate for temporary loss of insolation due to cloud cover and in order to allow extended operation into the evening hours when the demand on the utility grid is high.

GEO orbits for solar space power systems (SSPS) using STEC (those which are meant to beam power to Earth) are chosen such that sun occultation is minimal. For stations operating in LEO (with frequent sun occultation) and generating power for their own needs, the question of how to provide a constant power output by the on-board generator has to be answered. If the station uses STEC in LEO, a thermal energy storage buffer would allow the power plant to operate at constant output. The mode of thermal-to-electric conversion is irrelevant for the discussion here. It could be either a steam Rankine, mercury Rankine, potassium Rankine, or hot gas Brayton cycle for shaft power, or a thermoelectric generator. Whatever the temperature requirement of the conversion cycle may be, a thermal or thermochemical energy storage method can be found and adapted.

All applications listed above are of the load/input leveling type (Figure 2.48a). In addition to load leveling, energy storage can also be used to satisfy peak power demands (Figure 2.48b). In this mode of operation, storage is charged over a long period of time (probably several revolutions) and all accumulated energy is used to provide power for a short peak load, e.g., high intensity transmissions, communication with distance spacecraft or home base, or pulse power applications with beamed energy.

Although a Rankine or Brayton STEC power system is more complex than photovoltaic arrays, there are several potential advantages to such a system, in particular when it incorporates thermal storage: The system is not susceptible to radiation damage, and it could operate in orbits which are currently avoided by satellites because they pass through the Van Allen belts. This applies to orbits with constant altitude as well as to spiraling orbits flown by heavy payloads with electric propulsion for transfer from LEO to GEO. Furthermore, a STEC system can be built more

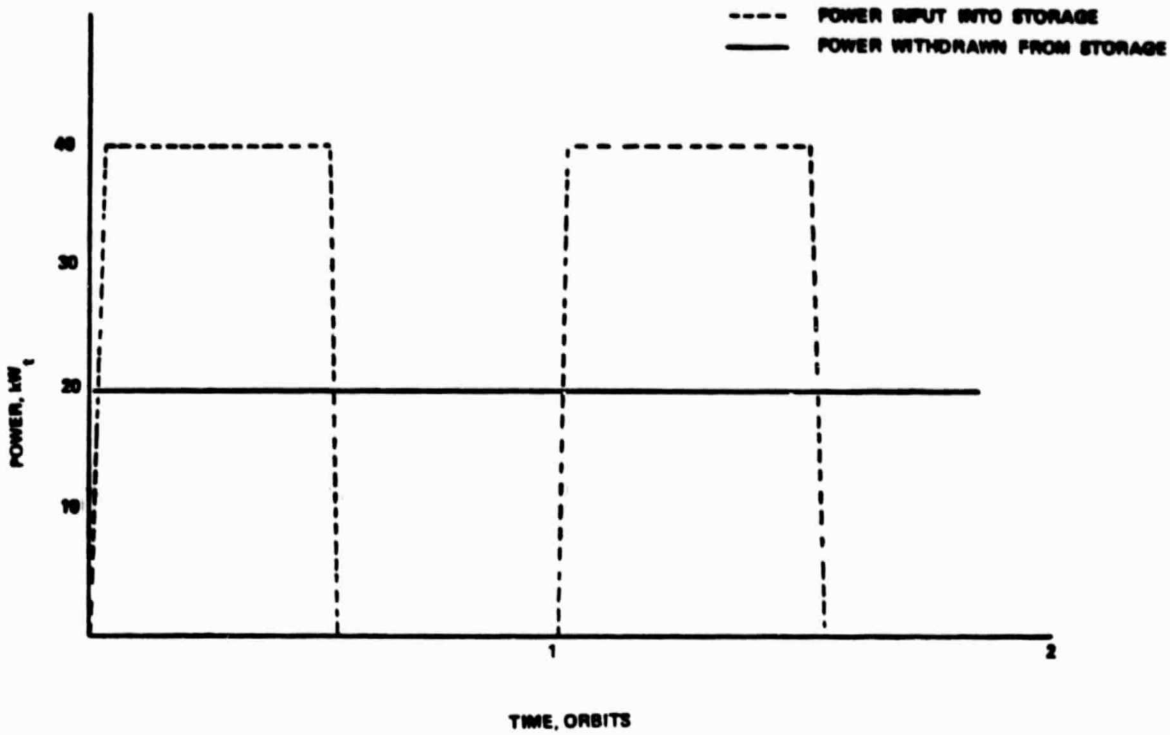

Figure 2.48 (a). Thermal Storage for Load Leveling.

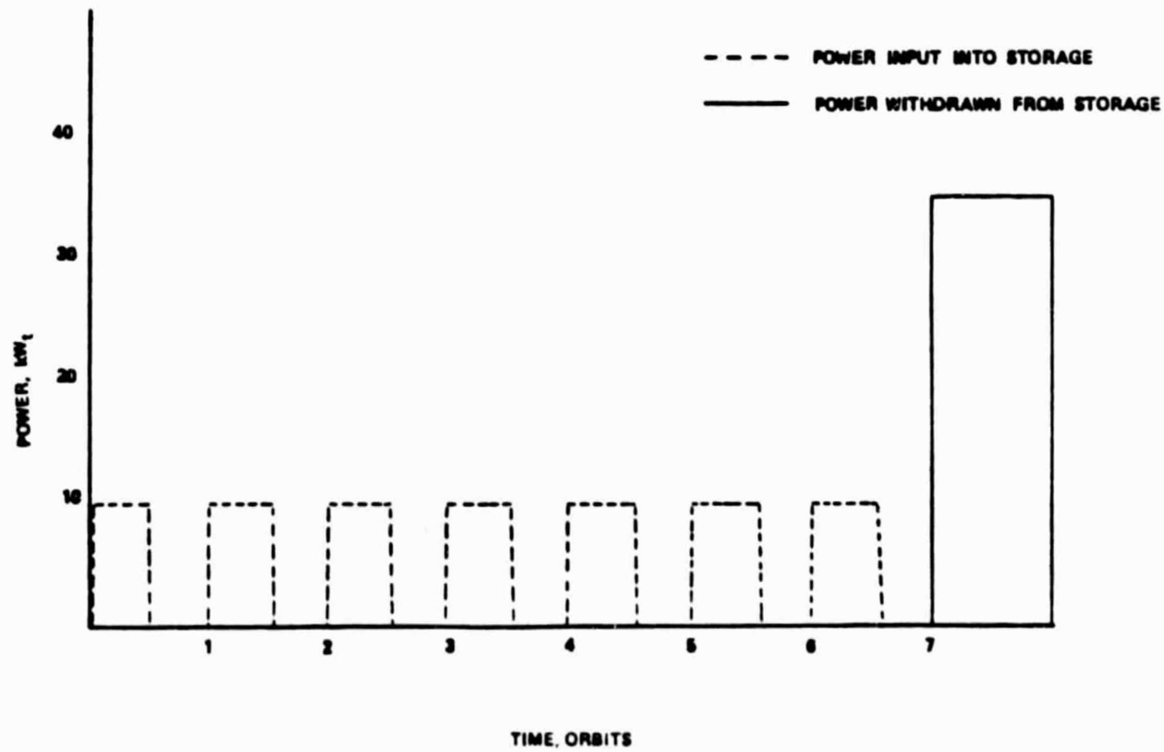

Figure 2.48 (b). Thermal Storage for Peak Power.

compactly than a solar PV array. It is less susceptible to atmospheric drag in the lower Earth orbits. It is also less likely to be detected by unfriendly forces because it would offer a smaller visual or radial cross-section. The rotating machinery reliability limitations would not apply to thermoelectric or thermionic converters.

THERMAL ENERGY STORAGE METHODS

Thermal energy storage methods include storage of heat in solids and liquids as sensible heat and in phase change materials (PCMs) as latent heat.

Both methods of energy storage are currently being evaluated for Earthbound stationary energy storage. PCMs have also been considered as energy storage for road vehicles. A common disadvantage of both sensible and PCM thermal energy storage is that because the storage media have to be stored in the hot state, heat losses are inevitable and the amount and quality of energy available decreases with time during periods of standby. These types of energy storage systems are therefore suitable for short-term storage only. Typical heat losses from large (>100 MWh), well insulated systems are of the order of 1%/day. For Earth orbit applications, such losses are nearly negligible. Vacuum in space will aid in achieving low thermal conductivities of multi-layer insulations. In addition, the absence of convection due to lack of gravity will eliminate one mode of heat transfer and heat loss. Heat losses by radiation and conduction will persist regardless of ambient pressure or gravity.

Evaluation criteria for thermal energy storage media are storage capacity (J/g) and storage density (J/cm^3). The energy storage system is characterized by the so-called roundtrip efficiency η_{RT}:

$$\eta_{RT} = \frac{\text{Energy out} - [(\text{parasitic power during discharge}) \cdot (\text{discharge time})]}{\text{Energy in} + [(\text{parasitic power during charging}) \cdot (\text{charging time})]}$$

This roundtrip efficiency is usually below 0.5 because of pressure drop, heat losses, and reduction of energy value ("availability") if the outlet temperature is below the inlet temperature. Roundtrip efficiency depends

on the mission duty cycle (charge:discharge ratio, charging time, degree of charge, discharge time, degree of discharge).

Up to this time, thermal storage systems were not extensively used on Earth because prime energy sources (coal, oil, gas) were thought to be abundant and used to be cheap. Only recently increased emphasis has been placed on thermal (and thermochemical) storage as a means to utilize cyclic energy sources (solar, industrial cyclic waste heat) or to make better use of existing power systems (load leveling and peaking power). This has resulted in recent advances in the state of the art, the implications of which have not yet been fully explored for potential space applications.

Sensible Heat Storage: Sensible heat storage systems have the disadvantage that heat is given off (and accepted during recharging) at varying temperatures; thus the discharging (charging) efficiency varies significantly with the state of charging. The amount of energy stored increases with the width of the temperature span within which the heat-using system can operate. Typically, the system requires the temperature to be as uniform as possible. Sensible heat storage systems are available for a wide range of temperatures ranging from hot water to hot oil, molten salts, or hot bricks. Molten salts are used extensively as heat transfer media (e.g., Hitec®) or heat treatment salts for the quenching and tempering of alloys ("draw salt"). A significant amount of data on molten salts has been accumulated as part of the evaluation of molten salts as coolants for nuclear fission reactors (Oak Ridge National Laboratory). Generally, the storage capacity of sensible systems is below that of either PCMs or thermochemical systems.

Phase Change Materials: As opposed to sensible heat storage systems, PCM heat storage systems operate at a more steady temperature. Ideally, the temperature band around the melting point within which the temperature fluctuates would be very narrow. In most practical cases, however, the temperature swing is wider and involves significant contributions of sensible heat from both the liquid and the solid phase. This is necessary because the thermal conductivity of the solid is so much worse than that of the liquid, and a temperature gradient of sufficient

magnitude has to be maintained in order to arrive at acceptable charge and, in particular, discharge rates. Heat exchanger tubes embedded in molten PCMs will usually be encrusted with solidified material as soon as heat is withdrawn from the system. The crust impedes heat transfer from the remaining hot liquid to the heat exchanger tube. Heat transfer enhancement methods are currently being developed for PCM applications. Under zero-g conditions it is important to keep the PCM in close contact with the heat exchanger tubes. A metal foam attached to the tubes would serve a dual purpose; not only does it enhance heat transfer because of good thermal conductivity of the metal, but it also retains the liquid by surface tension, similar to surface tension screens used in propellant tanks.

Several receivers for in-orbit solar thermal electric conversion with integral PCM storage have been developed and tested during the past decades. The SUNFLOWER mercury Rankine program at TRW tested lithium hydride PCM. Westinghouse tested a lithium hydride PCM storage device for a thermoelectric generator,[159] and NASA-Lewis tested a receiver with integral lithium fluoride PCM heat storage tubes surrounding the heater tubes for a Rankine or Brayton cycle power plant.[160-162] During the work with lithium hydride as a PCM, it was noted that the dissociation pressure at the melting point is substantial, and it was subsequently proposed to use the $LiH \rightleftarrows Li + \frac{1}{2}H_2$ system as an RCR heat storage system.

Chemical Energy Storage Methods: Chemical energy storage uses reversible chemical reactions (RCRs), e.g.,

$$A + B \underset{\text{endothermic}}{\overset{\text{exothermic}}{\rightleftarrows}} C$$

which can be easily reversed depending on concentration and temperature of the reactants. In the charging mode, chemical C is dissociated and the more energetic chemicals A and B are stored. Physical separation of A and B is not always required. A and B can be stored indefinitely without loss of stored energy. When energy is needed, A and B are allowed to recombine (generally on the surface of a catalyst) and energy is released in the reaction forming C. Thermochemical energy storage may be compared to the more conventional energy storage by pumped hydro where the dissociated

chemicals A + B constitute the more energetic state (upper reservoir) and C constitutes the lower energy state (lower reservoir).

The types of chemical energy storage being considered here for advanced space energetics include only thermochemical, photochemical, and radiochemical (fissio-chemical) reactions. Electrochemical energy storage is discussed in Section 2.3.7.1. The majority of information offered here for discussion is devoted to thermochemical storage via reversible chemical reactions (RCR). This mode of energy storage is relatively new, even for Earthbound applications, and its potential for space applications has not yet been fully explored.[163-165]

In addition to RCR chemical energy storage, RCR chemical energy transmission should also be considered, in particular where it can be integrated with chemical energy storage. These so-called "Chemical Heat Pipes" can replace conventional heat pipes where long distances of transmission are involved.[166]

Photochemical energy storage is taking place on a gargantuan scale on planet Earth in the form of photosynthesis. However, the energy storage density is extremely small. Photodissociation of nitrosyl chloride or isomerization of norbornadiene by concentrated sunlight has been attempted; the reverse reaction would then release heat. No practical system has yet been demonstrated, and it is very doubtful that photochemical energy storage/conversion holds any promise for space applications.

Radiochemical ("fissiochemical") energy storage is possible by irradiating ammonia with γ-rays, X-rays, electrons, protons, or other ionizing radiation, forming amino radicals which recombine to form energetic hydrazine. Hydrazine can be separated from ammonia and stored as the more energetic fluid. On Earth, synthesis of hydrazine from ammonia by passing it through a nuclear reactor has been demonstrated, but the process was not economical. It is suspected that the reaction is also taking place in the ammonia clouds of Jupiter's atmosphere. It is not expected to be a practical means of energy storage, even if the ionizing radiation is available for free, as in the Van Allen radiation belt.

It should be emphasized that thermochemical energy storage systems with reversible chemical reactions operate in a closed loop mode in a hermetically sealed system. Thus, under normal operation there are no consumables or replenishment chemicals involved. If the chemical reaction chosen is free from side reactions leading to irreversible byproducts, the reactants can be cycled back and forth an infinite number of times without losing storage efficiency.

Tables 2.22 and 2.23 provide a summary of selected reversible chemical reactions with their storage capacities and storage densities. The data have been arranged in two separate tables because the evaluation criteria for systems involving solid constituents are quite different from those for systems not involving solid reactants. Systems with solid reactants are difficult to scale up and solids handling is generally avoided if the same objective can be achieved with liquid reactants. Liquid reactants are more easily stored, metered, and pumped than solids. Gases, on the other hand, have very low storage densities.

The preferred thermochemical energy storage system would be one which involves only liquids in the charged as well as in the discharged state. Only one of the systems listed, the $SO_3(L) + H_2O(L) \rightleftarrows H_2SO_4(L)$ reaction, meets this requirement. Unfortunately, a high temperature separating technique for SO_3 and H_2O has not yet been perfected. The other all-liquid system, $H_2O(L) + H_2SO_4(L) \rightleftarrows H_2SO_4 \cdot H_2O(L)$, has too low an energy content to make its use attractive for space applications.

So far, Table 2.23 lists only saline hydrides such as lithium hydride. The energy changes associated with the formation and dissociation of metallic hydrides such as $LaNi_5H_6$ or $FeTiH_{1.9}$ are relatively small (7 kcal/mol H_2). These systems are being investigated mainly as a means to store hydrogen gas. Combination of two metallic hydrides operating at different characteristic temperatures in chemical heat pumps has been demonstrated. Chemical heat pumps will be discussed in a later paragraph.

Another method of chemical energy storage would be in the form of frozen free radicals, e.g., atomic hydrogen in a matrix of frozen molecular

Table 2.22

ENERGY CONTENT OF CANDIDATE CHEMICAL ENERGY STORAGE REACTIONS, EXCLUDING THOSE CONTAINING SOLIDS

Reaction exothermic $\rightleftharpoons$ endothermic	Reaction Enthalpy at 298°K		Temperature (°K) at which	
	J/g	J/cm³	90% Formed	90% Dissociated
$CO(G) + 3H_2(G) \rightleftharpoons CH_4(G) + H_2O(L)$	7,345	371	–	–
$CO(G) + 3H_2(G) \rightleftharpoons CH_4(G) + H_2O(G)$	6,053	306	754	1,466
$C_2H_4(G) + H_2(G) \rightleftharpoons C_2H_6(G)$	4,561	559	841	1,205
$2\ CO(G) + 2\ H_2(G) \rightleftharpoons CH_4(G) + CO_2(G)$	4,118	362	778	1,152
$CO(G) + 2\ H_2(G) \rightleftharpoons CH_3OH(L)$	3,996	248	345	434
$N_2(G) + 3\ H_2(G) \rightleftharpoons 2\ NH_3(L)$	3,861	189	–	–
$N_2(G) + 3\ H_2(G) \rightleftharpoons 2\ NH_3(G)$	2,695	132	346	528
$2\ NO(G) + O_2(G) \rightleftharpoons N_2O_4(L)$	1,750	362	549	930
$SO_2(G) + Air \rightleftharpoons SO_3(G)$*	1,544	1,692	806	1,270
$SO_2(L) + 1/2\ O_2(G) \rightleftharpoons SO_3(L)$	1,517	976	792	1,235
$SO_2(G) + 1/2\ O_2(G) \rightleftharpoons SO_3(G)$	1,235	794	792	1,235
$NO(G) + 1/2\ O_2(G) \rightleftharpoons NO_2(G)$	1,243	257	549	930
$CO(G) + Cl_2(L) \rightleftharpoons CO\ Cl_2(L)$	1,172	541	628	881
$SO_3(L) + H_2O(L) \rightleftharpoons H_2SO_4(L)$	885	1,442	535	723
$SO_2(G) + Air \rightleftharpoons SO_3(G)$	727	–	806	1,270
$NO(G) + 1/2\ Cl_2(L) \rightleftharpoons NO\ Cl(L)$	695	268	425	819
$H_2O(L) + H_2SO_4(L) \rightleftharpoons H_2SO_4 \cdot H_2O(L)$	230	327		

*Based on SO_2 weight only. Air open cycle

Table 2.23

ENERGY CONTENT OF CANDIDATE CHEMICAL ENERGY STORAGE REACTIONS, SYSTEMS WITH SOLID CONSTITUENTS

Reaction exothermic $\rightleftharpoons$ endothermic	Reaction Enthalpy at 298°K		Temperature (°K) at which $P_{Diss.}$ =		
	J/g	J/cm^3	0.1 bar	1 bar	$P_{Cond.}$
$Li(S) + 1/2\ H_2(G) \rightleftharpoons Li\ H(S)$	11,403	897	1,181	1,223	–
$Li_2\ O(S) + CO_2(G) \rightleftharpoons Li_2\ CO_3(S)$	3,029	2,899	–	–	–
$Na_2O(S) + CO_2(G) \rightleftharpoons Na_2\ CO_3(S)$	3,014	3,548	–	2,445	–
$Mg(S) + H_2(G) \rightleftharpoons Mg\ H_2(S)$	2,893	204	~500	560	–
$CaO(S) + SO_3(L) \rightleftharpoons CaSO_4(S)$	2,539	5,821	–	–	–
$CaO(S) + CO_2(G) \rightleftharpoons CaCO_3(S)$	1,776	2,239	1,028	1,171	>1,500
$MgO(S) + CO_2(G) \rightleftharpoons MgCO_3(S)$	1,387	1,576	610	670	850
$BaO(S) + CO_2(G) \rightleftharpoons BaCO_3(S)$	1,353	2,976	–	1,473	–
$NiCl_2(S) + 6NH_3(L) \rightleftharpoons [Ni(NH_3)_6]\ Cl_2(S)$	1,347	1,515	–	–	–
$NH_3(L) + H_2SO_4(L) \rightleftharpoons NH_4{\cdot}HSO_4(S)$	1,256	1,774	–	–	–
$[Ni(NH_3)_2]\ Cl_2(S) + 4NH_3(L) \rightleftharpoons [Ni(NH_3)_6]\ Cl_2(S)$	1,048	–	–	–	–
$KF(S) + (HF)_n(L) \rightleftharpoons KHF_2(S)$	1,031	1,813	600	725	730
$CaO(S) + H_2O(L) \rightleftharpoons Ca(OH)_2(S)$	880	1,861	722	820	676
$NaF(S) + (HF)_n(L) \rightleftharpoons NaHF_2(S)$	832	1,431			
$MgO(S) + H_2O(L) \rightleftharpoons Mg(OH)_2(S)$	644	1,280	495	555	465
$BaO(S) + H_2O(L) \rightleftharpoons Ba(OH)_2(S)$	598	2,283	1,052	1,271	961
$FeCl_2(S) + 6NH_3(L) \rightleftharpoons [Fe(NH_3)_6]\ Cl_2(S)$	302	326	–	390	
$CaCl_2(S) + 6NH_3(L) \rightleftharpoons [Ca(NH_3)_6]\ Cl_2(S)$	210	202		310	

hydrogen. This possibility has already been investigated for a long time, but it is unlikely to become available as mature technology in the near future.[167-169]

Table 2.24 summarizes energy storage capacity and storage density for typical thermal and thermochemical energy storage media. So far, numbers shown in Table 2.24 are for the storage media only. This is like showing only the electrolyte and electrode weight of a battery without casing, spacers, and insulation. Weights or volumes for containment of thermal/thermochemical storage media, heat exchangers, pumps, and other process equipment have not yet been included.

The main reason for not yet including system weights in the table is that no reliable numbers are available at this time. Thermal energy storage technology for Earth based applications is just emerging, and high temperature thermochemical systems exist only as a concept. If currently available data were used and if the data were applied to potential space applications the results would be misleading since the designs for Earth based systems were done with little concern for system weight or system volume. Lightweight structural materials such as those typically used for spacecraft would result in more favorable system weights. Also, if large systems were assembled in space and had to withstand neither 1 g nor high g forces during launch, the support structure would be much lighter than the same system intended for Earth based applications.

The preliminary design of thermal and thermochemical energy storage systems for space applications requires additional effort to come up with reliable predictions and performance comparisons. The same is true for cost data for any of these systems because there is no cost experience.

The system weights to be added to the storage media weights depend on the desired charge:discharge power ratio. They would be optimal if the charge:discharge ratio were kept close to 1.0. The system weights in relation to the storage medium weight for a given total storage capacity and charge:discharge ratio are small for sensible, larger for PCM, and significant for thermochemical energy storage systems. The complexity of

Table 2.24

Storage Capacity and Storage Density of Heat Storage Media

	Typical Operating Temperature °K	Storage Capacity J/g	Storage Capacity W-hr/lb	Storage Density J/cm³
Sensible Heat Storage ΔT = 200 °K				
Hot Oil (Therminol 66)	400-600	526	66	405
Molten Salt (Partherm 430)	600-800	310	39	510
MgO Bricks	800-1000	250	32	900
Phase Change Materials				
Sodium sulfate decahydrate (Glauber Salt)	305	234	29	375
Hitec®	658	460	58	750
Fluoride Eutectic (67 wt. %LiF/33 % MgF_2)	1119	908	114	1960
Lithium Fluoride	1121	1044	132	1910
Thermochemical RCR				
$Li(S) + \frac{1}{2}H_2(G) \rightleftarrows LiH(S)$	1100-1200	11,403	1437	897*
$\frac{1}{2}O_2(G) + SO_2(L) \rightleftarrows SO_3(L)$	790-1200	1517	191	976*
$SO_3(L) + H_2O(L) \rightleftarrows H_2SO_4(L)$	500-700	885	115	1442

*Gases compressed and stored at 152 bar at 298 °K.

most thermochemical energy storage systems is only warranted for very large installations (>100 kW) and long storage times. For a short term (less than 6 hours) storage system operating at a charge:discharge ratio of 1, the system weight roughly equals the weight of the storage medium for sensible and PCM storage, and is roughly twice the weight of the storage media for a thermochemical system. This reduces the weight-specific numbers in Table 2.24 by a factor of 0.5 to 0.3.

If one envisions the use of thermal or thermochemical storage in conjunction with thermal-mechanical-electric conversion, the numbers will furthermore have to be multiplied times a factor of 0.2 (20 percent conversion efficiency assumed for thermal to mechanical conversion). If the conversion from stored chemical to electric energy is carried out in fuel cells instead of a mechanical turbine, the storage capacity of chemical systems would be higher and above that of Ni/H_2 batteries serving as a benchmark for comparison.

The entire field of storage media for sensible, PCM, and thermochemical energy storage systems has been thoroughly searched. It will be difficult to find other, new storage media which will result in significant improvements over the examples listed in Table 2.24.

The cycle life of sensible and PCM heat storage media is essentially unlimited. The life of the heat storage system is most likely limited by the life of centrifugal pumps used to circulate heat exchange fluids or heat storage fluids. Thermochemical systems not involving solids generally require a catalyst and/or separating membranes. It is estimated that current technology catalysts limit the useful life of the system to approximately ten years. The catalyst can be replaced during maintenance of the system.

Chemical Heat Pumps: In addition to plain energy storage, reversible chemical reactions are also being used to collect heat at a low input temperature and to release it (although a smaller amount) again at a higher output temperature, analogous to an evaporation/condensation mechanical heat pump. Reactions which are being evaluated for this purpose

include hydrides[170], ammoniates[171], and sulfuric acid/water.[172] It has been proposed to use mechanical or chemical heat pumps on satellites to boost waste heat temperature to a higher outlet temperature such that it can be radiated and rejected by more compact radiation.

Because the amount of energy radiated increases with the fourth power of the radiator temperature, the overall system might be lighter than without heat pumping. Under terrestrial conditions it is usually easy to find a heat sink for a heat pump. This is not as easily done in a space environment.

Chemical Heat Pipes: In addition to storing and pumping energy, reversible chemical reactions can also be used for transmission of heat from Point A to Point B. The unique feature of chemical heat pipes is that the reactants are transported at ambient temperature. Unlike a steam or hot oil pipeline, there are no thermal losses during transport. A chemical heat pipe is therefore attractive for transmission of heat over very long distances. Chemical heat pipes can be used to distribute heat from a central heat source[173] or to collect heat from a multitude of parabolic dish focusing collectors[174] with or without buffer storage of reactants.

For a large power satellite in geostationary orbit, the system could be modularized and could be assembled from a large number of easily transported small parabolic concentrators. In the focal point of each collector there is a thermochemical receiver in which the heat is used to dissociate a chemical in an endothermic reaction. The dissociation products are collected in a manifold and fed to a central exothermic reactor with the adjacent central power plant. This system promises to be more efficient than a multitude of dish-mounted heat engines.

Comparing the performance, weight, and cost trade-offs of competing thermal and thermochemical energy storage technologies is not as easy as comparing the merits of different types of well established electrochemical storage devices, e.g., nickel-silver versus nickel-hydrogen versus reversible fuel cells. There are not sufficient design data available for existing systems, and those which are available are only for terrestrial

utility-sized systems. In order to compare thermal and thermochemical storage technology with competing storage techniques, one has to rely on a number of assumptions and extrapolations. Three such comparisons published in the literature shall be referenced here in order to emphasize the conclusion that thermal (and thermochemical) energy storage should receive further study for space advanced energetics. Not all assumptions underlying the three studies are known at the present, and it would occupy too much space to spell them out here.

The 25 kW space station study by Grumman(175) compared system mass penalties for two different storage requirements: 30 kW peak load with Brayton conversion (Figure 2.49) and 130 kW eclipse load with thermionic conversion (Figure 2.50). In both cases the system mass penalty was lowest with a lithium fluoride PCM thermal storage system.

A British study(176) compared the storage density (GJ/m^3) and storage capital cost (£/GJ) of various storage technologies (Figure 2.51). Reversible chemical reactions and fused salts had the best cost and density characteristics of all systems considered (excluding the air-supported combustion of fuels such as oil and synthetic hydrocarbons).

A comparison of storage technologies for utility energy storage (systems above 100 MW_t) shows the dependence of capital and storage cost on the time of operation on storage (Figure 2.52).(177) Because the cost lines start out at different capital costs (zero storage) and because the slopes of the lines differ, the best storage technology depends on the desired mission profile. This chart assumes that the system is discharged immediately after being fully charged and does not make allowances for energy lost during standby. Underground pumped hydro and compressed air combustion gas turbines cannot be applied in space stations. This essentially leaves PCMs (fluoride eutectic) as the most economical option for storage capacities up to 10 hours.

Summary: It appears that thermal or thermochemical energy storage will not play an important role in space operations as long as space vehicles remain the size of a single Skylab, Spacelab, or Space Shuttle,

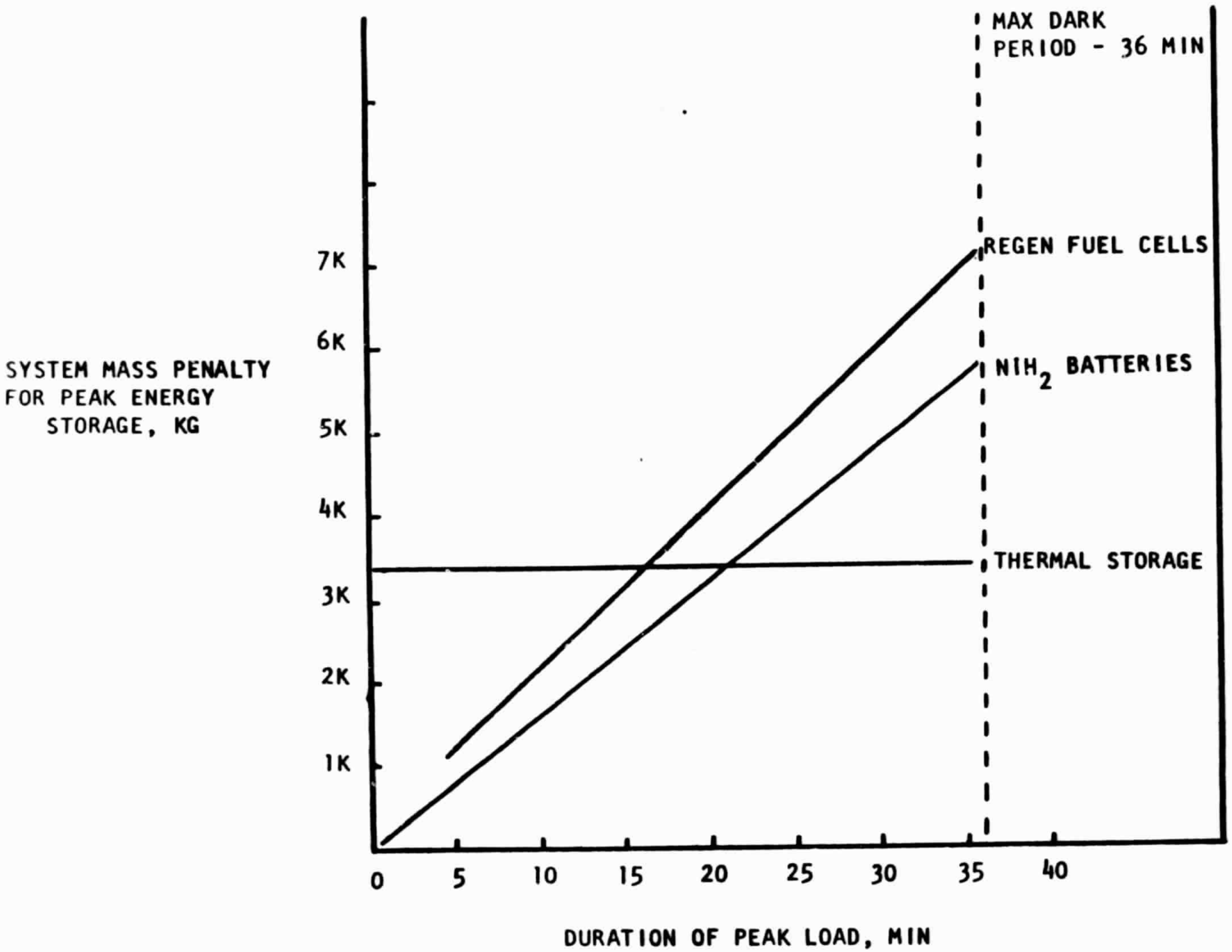

Figure 2.49. Solar-Brayton Energy Storage for 30 KW Peak Load (Reference 175).

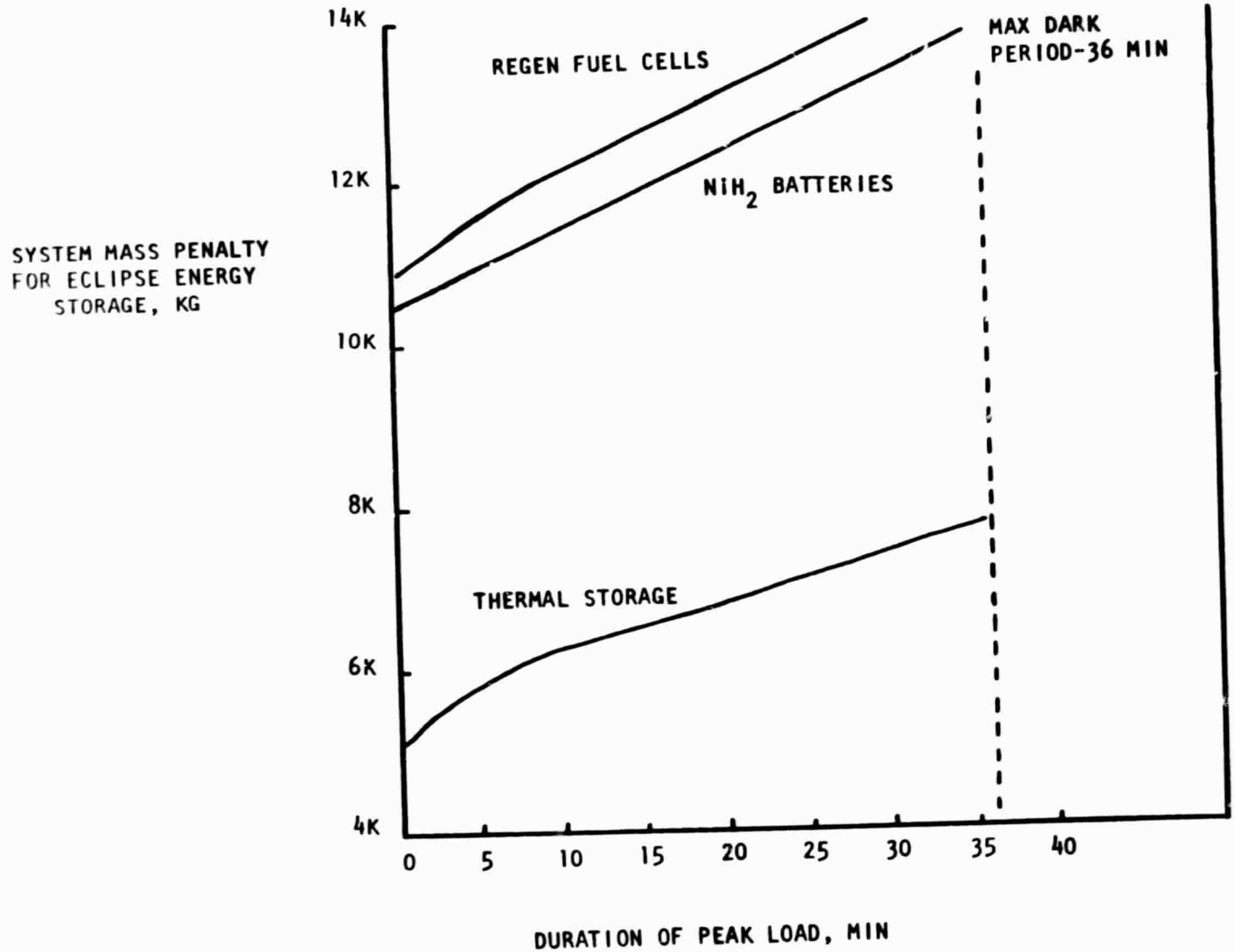

Figure 2.50. Solar-Thermionic Energy Storage for 130 KW Eclipse Load (Reference 175).

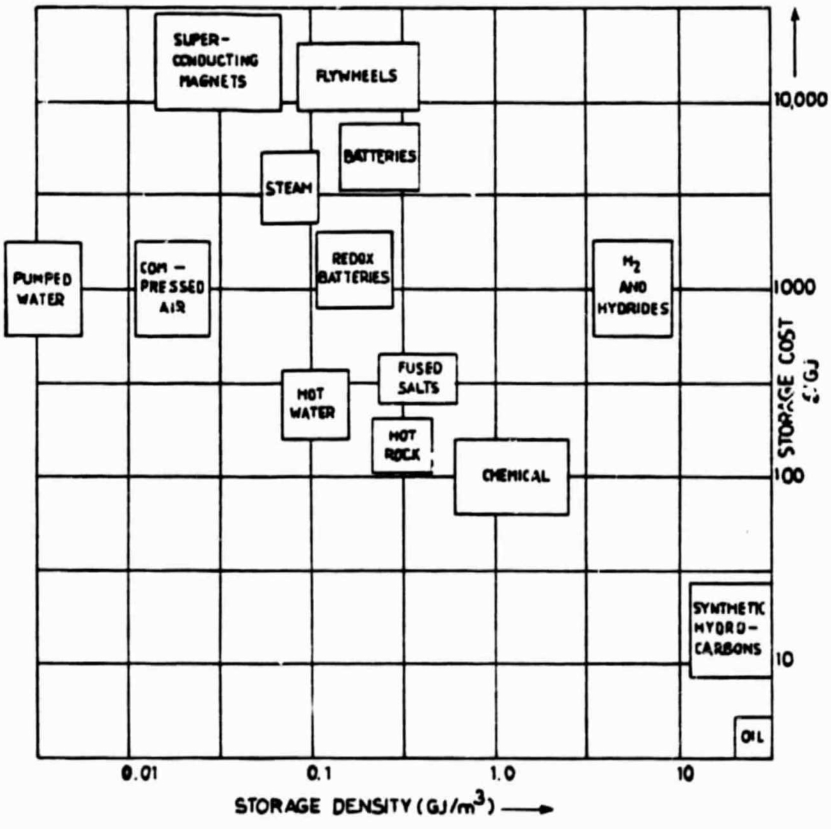

Figure 2.51. A Comparison of Various Energy Stores in Terms of Capital Cost and Storage Density. The costs of producing and distributing energy are excluded. (Reference 176)

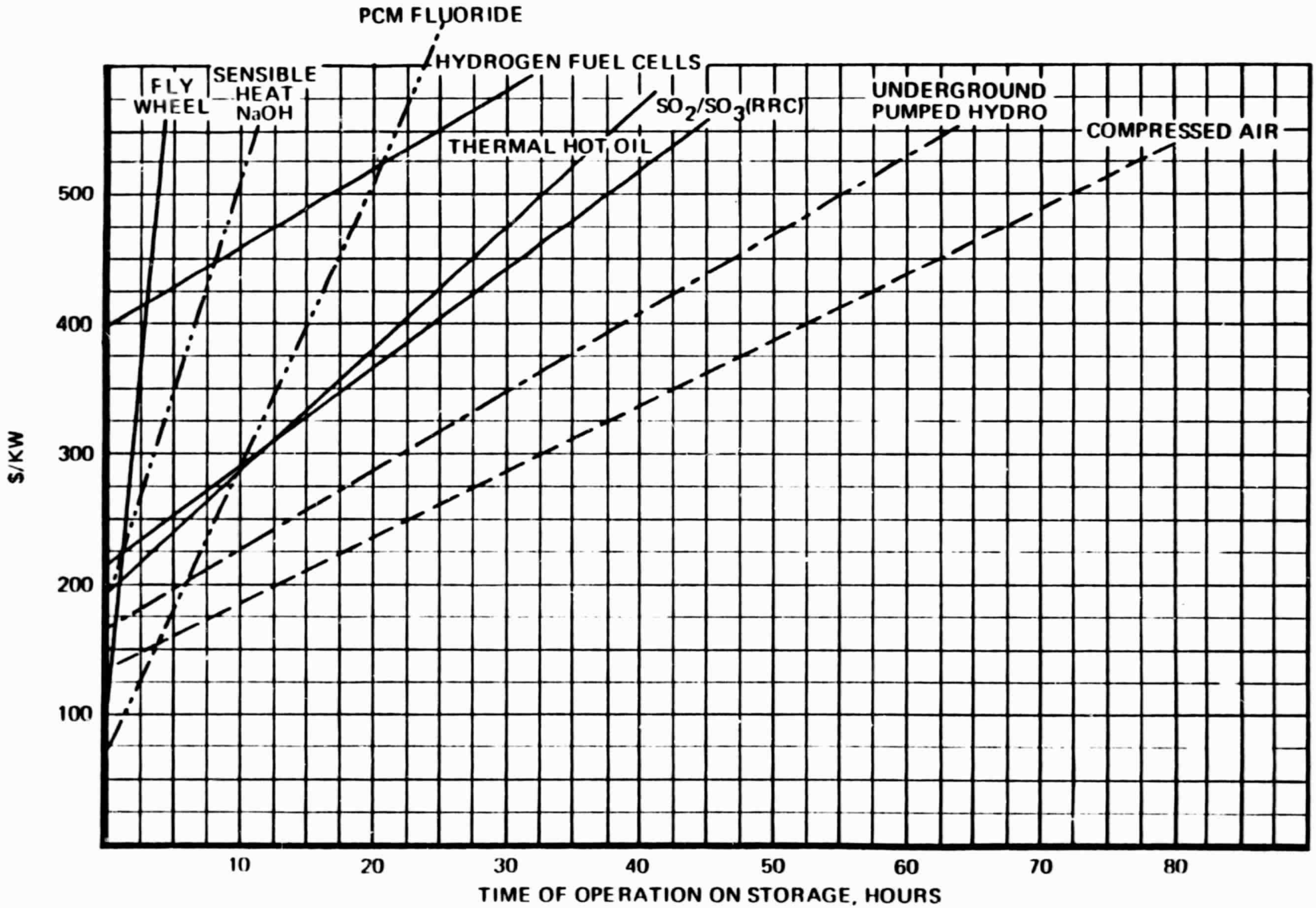

Figure 2.52. **Preliminary Comparison of Investment/Storage Costs of Energy Storage.**
(Reference 177)

the reason being that small thermal requirements are more easily met with electric resistance heaters. Thermal electric conversion via mechanical does not become attractive until power levels of at least 20 kW are required. If it should be used, short term thermal storage will enable the system to operate throughout the entire orbit and, in particular, during sun occultation. Thermochemical energy storage is not attractive unless very long storage times (in excess of 24 hours) are required. It would be ideally suited for lunar bases with very long dark periods (14 days).

Several experts in the field of thermal and thermochemical energy storage have been interviewed and asked if they were aware of any past or ongoing research and development efforts in thermal or thermochemical energy storage for space applications. Several useful leads to past work were obtained, but none of the persons were aware of any thermal/thermochemical storage work in progress for space applications.

2.3.7.5 Novel Approaches

So far, energy storage has been considered as a pure storage method only, with identical forms of energy input and energy output. Certain improvements in overall systems efficiency are possible by combining energy storage with energy conversion.

Thermally Regenerative Fuel Cells

A thermally regenerative fuel cell uses a reversible thermochemical/electrochemical reaction. The endothermic step of the reaction is carried out in the focal point of a solar concentrator, e.g.,

$$SO_3 + \Delta H \rightarrow SO_2 + \tfrac{1}{2} O_2$$

The dissociation products can then be stored indefinitely until electric energy is needed. The exoergic reaction with electron transfer takes place on the electrodes of a fuel cell, releasing electric energy and oxidizing SO_2 to SO_3:

$$O + 2e^- \rightarrow O^{--}$$

$$S^{+4} - 2e \rightarrow S^{+6}$$

Thermally regenerative fuel cells are not limited by Carnot efficiency. No experimental data are available yet. Thermally regenerative fuel cells should not be confused with regenerable (= reversible) fuel cells where both energy input and output are in the form of electric energy. Several reversible chemical reactions are currently being evaluated for potential use in regenerative fuel cells.

So far, fuel cells for aerospace have always been associated with hydrogen/oxygen fuel cells. Sufficient know-how exists with oxygen/hydrogen fuel cells for space applications. Unfortunately, the oxygen and hydrogen reaction

$$O_2 + 2H_2 \rightarrow 2H_2O$$

is highly irreversible. Thermochemical water splitting cycles are under development, but the conversion efficiency of multi-step water splitting processes resulting in hydrogen and oxygen is very poor. While hydrogen/oxygen fuel cells achieve conversion efficiencies of 60 percent, the overall efficiency of a thermally regenerative hydrogen fuel cell would be below 10 percent. So, even if the SO_2 + O_2 fuel cell should be only 30 percent efficient, it would still be better than the combined efficiency of most other systems which convert to electricity first and then store electricity, or store heat first and then convert to electricity. In attempting to sell the idea of the SO_2 fuel cell to prospective sponsors for further development, the SO_2 fuel cell has so far not made any inroads, because people already working on fuel cells always compared it to the oxygen/hydrogen fuel cell (assuming that hydrogen is readily available when, in reality, it is not). By comparing the fuel cell efficiency only, the SO_2 fuel cell cannot stand up to the hydrogen fuel cell. It is the combination of thermal to electric conversion which makes this scheme now so attractive.

Thermal Storage in Brayton Power Cycles

Thermal storage is an attractive alternative to other modes of energy storage for Brayton power cycles. The stored high temperature thermal energy can be used as a heat source during periods when extra electric power is required.

A graphite particulate bed will store 1 MJ(th) per kg for a ΔT of 500 ^{o}K. The Brayton cycle expander could run at constant temperature with variable recirculation flow being used to accomodate the changing source temperature during those periods when the thermal storage bed was being drawn again.

For a power cycle efficiency of 30 percent over the draw down period, a graphite particulate bed could store ~100 watt hours(e) per kg. This compares very favorably with advanced batteries and is considerably better than present battery systems. The number of cycles would be essentially unlimited, and no degradation of storage capability should occur. Graphite also has the potential advantage of extending the operating temperature of Brayton cycles with energy storage up to 1500 ^{o}K if the interaction of the carbon with the turbine materials is not too deleterious.

The prime energy source would be sized for the average power of the cycle, while the energy conversion device (e.g., a turbine) would be sized for the peak power. The energy source would have to be capable of short periods of operation at substantially higher temperatures (e.g., 500 ^{o}C higher than the normal operating temperature). This might not be feasible for some sources; however, for gas cooled reactor or solar thermal systems, it appears likely that the outlet coolant temperature capability is considerably higher than can be accepted by a turbine.

Thermal Electrochemical Energy Storage

Near-reversible electrochemical energy storage is a very promising storage option for space power applications. Systems have been developed in which units can function first as electrolyzers to dissociate chemical

compounds, and then as fuel cells to generate electricity when the products are recombined. The very high specific energy available per unit mass of the dissociated compounds makes this storage option much more attractive than batteries.

A leading candidate is a high temperature (~1000 ^{o}C) solid oxide electrolyzer/fuel cell assembly operating on steam/hydrogen and oxygen. The steam/H_2-O_2 system has an energy storage density of 2600 watt hours (e)/kg of stored H_2/O_2 at an efficiency of 70 percent in the fuel cell mode. This is an order of magnitude better than can be achieved with advanced batteries.

Solid oxide electrolyzer/fuel cell assemblies have been developed and tested in the U.S. by Westinghouse, in West Germany by Dornier, and in Switzerland by Brown Boveri. The cells consist of several layers of thin films, each with a typical thickness of ~10 , deposited on the surface of a porous yttria stabilized ZrO_2 tube. Typically, the tube has a wall thickness of ~0.5 mm and a diameter of ~1 cm.

The successive thin film layers consist of an outer O_2 electrode, a sandwiched electrolyte (yttria stabilized ZrO_2), and an inner H_2 electrode. The electrodes are connected in series along the ZrO_2 tube using thin interconnection films. The electrodes, electrolytes, and interconnection films are deposited using masking techniques similar to those in the electronic industry, with chemical or vapor deposition.

Single and small stacks of multiple cells have been tested for thousands of hours at operating temperatures of ~1000 ^{o}C. Large arrays have not yet been tested, but there appear to be no fundamental problems in constructing large systems. Mass production fabrication techniques will have to be developed, however.

Achievable output power densities for H_2/O_2 solid oxide electrolyzer/ fuel cells are ~0.35 watts (e)/cm^2 (0.5 A/cm^2, 0.7 volts). While operating in the electrolyzer mode at 1000 ^{o}C, input electrical requirements are ~0.55 watts/cm^2 (0.5 A/cm^2, 1.1 volts) with corresponding thermal inputs of ~0.3 watts per cm^2. For tube wall thicknesses of 0.5 mm,

gross specific powers will be ~1000 watts(e) per kg mass of the solid oxide assembly.

For a given power delivery time τ_C, the equivalent specific energy storage for the electrolyzer/fuel cell assembly is 1000 τ_C watt hours(e)/kg. Thus, for values of τ_C of 3 to 4 hours, the energy capacity in watt hours(e)/kg will be comparable to that for the stored H_2/O_2, i.e., ~2600 watt hours(e)/kg. The overall specific energy storage for the entire system is:

$$\frac{1}{S_T} = \frac{1}{2600} + \frac{1}{1000\,\tau_C} + \frac{1}{S_C} \qquad \frac{\text{kg}}{\text{Watt-hr(e)}}$$

where S_C = watt hours(e) per kg of mass for the container for the stored H_2 and O_2 gas. For optimized storage systems, S_C will be on the order of twice the value for H_2/O_2 alone. Accordingly, for power delivery times of 3 to 4 hours, S_T is ~1000 watt hours(e) per kg of total mass, and substantially higher for longer power delivery times.

Electrolyzer/fuel cell stacks could readily be arranged in series/parallel connections to match the output characteristics of solar or other power source arrays, and should not require any power conditioning.

Another promising candidate would be the H_2Cl system using cells with solid polymer electrolytes (SPEs) at ~100 ^oC.[55] The much lower operating temperature with this system poses more problems of heat removal than the 1000 ^oC H_2/O_2 system, but it appears practical. A similar HBr system is to be tried on the space shuttle. No heat would be generated during charging because of the $T\Delta S$ term; on discharge (recombination of H_2 and Cl_2 to generate electricity), however, ~0.7 watt of heat would be produced per watt of electrical output, and this would have to be radiated to space at a radiator temperature of ~400 ^oK.

Typical performance parameters would be ~0.3 A/cm^2 at 1.2 volts. The SPE would be ~10 mils thick, with an overall thickness of ~4 mm per cell. Cell electrodes would use carbon based materials.

The HCl system does not appear as attractive as the H_2/O_2 system because of higher electrolyzer/fuel cell weight per unit output, lower operating temperature, and a somewhat higher weight of stored gases per unit amount of stored energy.

2.3.8 Energy Storage Conclusions

Batteries are the principal energy storage technology for spacecraft at present. However, the demands for longer lifetime, greater number of charge-discharge cycles, lighter weights, and greater net energy storage capacity will require substantial advances over the performance of present systems. New and advanced battery concepts are available which appear to have the capability to meet these requirements. In addition, flywheel storage, regenerable fuel cells, thermal storage, thermochemical storage, and several novel concepts integrating energy storage with energy conversion promise significant advances in these areas.

Advanced nickel hydrogen batteries, silver hydrogen batteries and high temperature batteries offer good prospects for significant improvement over current energy storage. Regenerative fuel cells using either bifunctional electrodes or separate electrolyzers and fuel cells also look attractive in terms of weight for medium to high power systems (e.g., 25 kW and above). Flywheel energy storage appears to be applicable by itself and possibly in combination with attitude control. It may be possible to combine the flywheel energy storage function with inertial attitude control functions to economize on weight for particular missions. Flywheels look particularly attractive wherever high power density is desired (i.e., watt/lb). Further, they have exceedingly long self-discharge times compared to virtually any other energy storage technology (i.e., potentially 5 to 10 years).

Thermal or thermochemical energy storage is best suited for medium to high power systems (i.e., 25 kW and above) since thermal requirements can be easily met by resistance heaters at low power levels. Also, thermal energy conversion becomes truly competitive with photovoltaics for power above 25 to 50 kW and will be able to utilize thermal energy storage

effectively. There is also an intriguing possibility that the integration of some energy storage and conversion concepts may offer higher performance than the separate use of high performance storage and high performance conversion technologies.

As a result of the technical assessment of energy storage technologies, the following items are recommended for further research. These recommendations will be narrowed considerably in Section 5 in order to arrive at the highest priority items for NASA's Advanced Energetics Program.

RECOMMENDED BATTERY RESEARCH

1. Research, at a modest level, is needed on nickel-cadmium batteries to better understand their problems and weaknesses, and to improve the technology. A nickel electrode research program would benefit both nickel-cadmium and nickel-hydrogen battery technologies.

2. An analysis is needed to determine energy density that could be attainable with R & D on nickel hydrogen batteries. This will help in determining how much emphasis should be given to nickel-hydrogen research.

3. A nickel electrode basic research program is needed. This should include a comprehensive review of the nickel electrode.

4. An advanced nickel-hydrogen technology program is needed.

5. A silver-hydrogen research program is needed which includes monitoring of silver-hydrogen battery research in Europe.

6. A study should be made of all candidate high temperature battery systems to determine realistic energy densities to be expected and to determine those systems most deserving of research. This should include couples currently not under development.

7. Expertise is needed in high temperature batteries and the establishment of a long-range research program in this area would be beneficial.

8. There is a need to establish a program on super ionic solid state conductors for use in development of high temperature batteries.

9. Methods should be developed for monitoring batteries and determining their state-of-health. This should be applied to the development of autonomous operation of battery systems.

10. Lightweight switching devices should be developed for reconfiguring battery cells, battery modules, chargers, and other components when failures occur.

11. Research on safety should be conducted on those lithium battery systems currently planned for NASA manned missions, such as the shuttle.

12. Research should be performed to develop a non-destructive state-of-charge test for lithium primary cells.

13. Aerospace quality primary lithium cells should be developed for electronics memory retention applications.

14. A small program should be undertaken to seek out and conceive new battery concepts which have promise as high energy density spacecraft batteries.

RECOMMENDED FLYWHEEL RESEARCH

1. Advanced high energy-density rotors should be designed for a size representative of some realistic applications.

2. Advanced materials for rotors should be investigated.

3. A study of total system integration needs to be carried out, using the most advanced available rotors, to combine the development of rotor dynamics, bearings, control electronics, motor-generators, and other extraction techniques.

RECOMMENDED THERMAL AND THERMOCHEMICAL ENERGY STORAGE RESEARCH

1. Summarize thermal power needs of space processing operations. Review that list for thermal storage applications.

2. Integrate energy requirements of life support systems with thermal/thermochemical energy storage systems.

3. Perform a set of preliminary baseline designs specifically for in-space (vacuum, zero-g) operation of one each (a) sensible, (b) PCM, and (c) thermochemical energy storage system to obtain performance, weight, and cost data for several specific applications/missions.

RECOMMENDED NOVEL APPROACHES

1. Study the feasibility of thermal regenerative fuel cells as a confined energy storage and conversion technology for space.

2. Investigate fluidized bed energy storage concepts (e.g., graphite particulates) for high temperature gas, thermal energy conversion such as the Brayton cycle.

2.4 Power Transmission

2.4.1 Introduction

Power transmission encompasses power beaming to spacecraft from remote sources (i.e., orbiting or planetary-based power stations) and waste heat radiators. Power beaming is primarily conceived of as electromagnetic energy (e.g., laser or microwave) transmitted in phase at a single frequency with a very small beam divergence so that tuned receivers of a modest size can convert the incident radiation with high conversion efficiency. Laser and microwave beam sources are discussed briefly below, including a brief review of the state of the art for beam power transmission. The main problems with long distance power transmission are beam divergence, atmospheric effects (in the case of ground-based power

transmitters), and high intensity optics needed to form, transmit, receive, and refocus the beams. Tuned receivers are also reviewed; these devices can capitalize on the monoenergetic character of the radiation to achieve high efficiency conversion.

Waste heat radiators, in contrast, involve incoherent, nearly isotropic radiation emission under conditions normally approximated by a blackbody source at an effective radiation temperature, T_{rad}. Current spacecraft radiator technology depends almost entirely upon flat plate radiators. Plate and fin radiators are strictly passive and involve heat conduction from the heat source through the spacecraft's structure to an exterior portion of the spacecraft, which acts as the radiator. As higher powers are developed, the radiator will grow in size and weight. Radiators comprise a significant portion of thermal power systems weight and, hence, an aggressive program to reduce radiator weight, especially at higher powers, is needed. Options at higher powers include heat pipes, pumped fluid radiators, and more advanced radiator concepts.

2.4.2 Requirements

Coherent, phased power transmission using diffraction-limited beams can be effective over large distances. Specifically, the transmitting and receiving antenna diameters (D_t and D_r, respectively) are governed by the relation $D_t D_r = C_1 \lambda R$ where R is the range, λ is the wavelength, and C_1 is a constant related to the fraction of incident beam profile intercepted by the receiving antenna.[178] The product $D_t D_r$ is shown in Figure 2.53 for several different wavelengths. Figure 2.53 indicates that power could be transmitted as far as the moon using small antennae if short enough wavelengths are used. However, beam power transmission is not presently in use. The nearest related use of this technology occurs in remote laser sensing and communications where similar relationships apply and where relatively small powers are needed. Although mission analysis of beam power transmission is outside the scope of this study, a great deal of analysis in this area has been carried out for the solar power satellite (SPS) application. A beam power transmission study parallel to the present

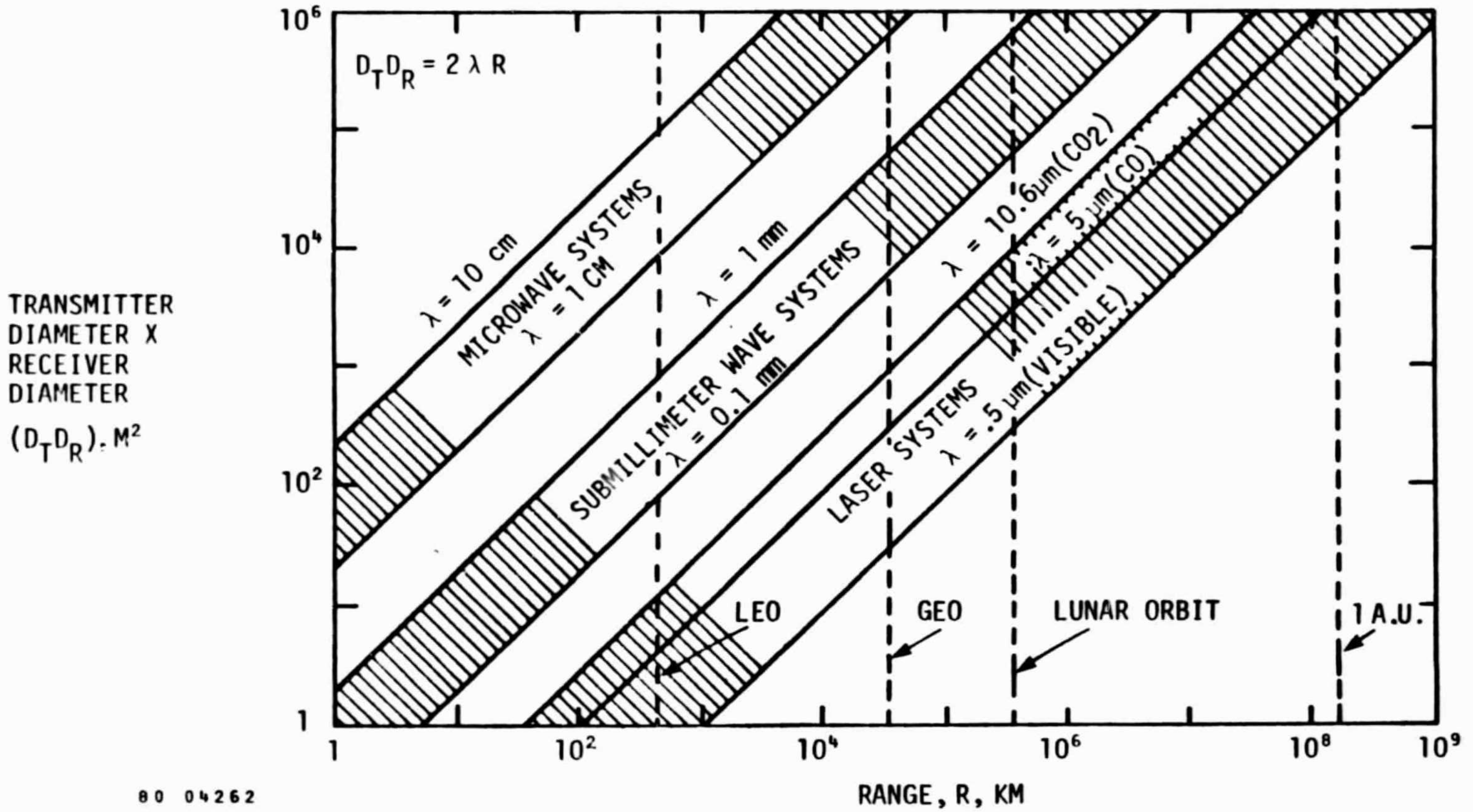

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Figure 2.53. Transmitter/Receiver Sizes versus Range.

energetics study is also being carried out, which will encompass a preliminary mission analysis. Gigawatts of power from a single transmitter have been considered for the SPS application, with receiving antenna several kilometers on a side required on Earth.[179-181] Future high power space-to-space power transmission, for example to power electrical propulsion systems used for orbital transfer, may require tens of megawatts of power using receiving antennas no more than tens to hundreds of meters in diameter.[182] Smaller power requirements in the range of a few hundred kilowatts to Megawatts may be required for satellite power supplies, with receiving antenna size dependent on the mission environment.

The receiver-converter may also be sensitive to the frequency used, and safety requirements may further limit the frequencies used. For example, microwave levels must be kept below 10^{-3} watts/cm^2 under present United States statutes, and laser wavelengths must be greater than approximately 2 microns in order to prevent eye damage. (Industrial safety standards for laser use are much more detailed according to the frequencies and the peak power levels encountered in pulsed lasers.)

Safety and efficiency of conversion may also require accurate power beam tracking and pointing to avoid "spill over" beyond the receiving antenna. The D_tD_r relationship discussed above assumes that the receiving antenna accepts 95% of the incident radiation; further, the transmitter is assumed to operate in phase so that side lobes constitute a relatively small fraction of the transmitted power.

Waste heat radiators generally are sized to reject power at levels of 3 to 9 times the net electric power being produced on-board the spacecraft, as the efficiency may be as high as 25% or as low as 10%, respectively. In the case of photovoltaic cells, waste heat must be radiated at low temperatures in the range of 28 °C to 50 °C, since the efficiency of photovoltaic cell material is substantially reduced at higher temperatures. The exception will be high concentration ratio solar cells where higher operating temperatures on the order of 130 °C may be encountered. Radioisotope power sources require waste heat radiators which operate at temperatures in the range of 50 °C to 180 °C. A need for higher

temperature radiators in the range of 200 °C - 1400 °C is anticipated as higher power systems become necessary, in order to keep the radiator weights and sizes as small as possible.

2.4.3 Power Transmission Methods

The following paragraphs give a brief description of beam power transmission and waste heat radiator methods. Power transmission is still basically at the conceptual stage, so nothing definitive can be said about what techniques will work. Waste heat radiators, usually of the passive variety, are associated with each power system in space, and there is an accepted state-of-the-art technology in this area.

2.4.3.1 Microwave and Millimeter Phased Arrays

Microwave beam power transmission at wavelengths of 10 cm or longer (suitable for atmospheric transmission) can be carried out with a variety of rapidly pulsing vacuum tube devices, such as the klystron, which drive microwave horn or slot transmitters and are received by dipole-filter, half-wave microwave rectennas. Initial experiments have demonstrated overall transmission efficiencies exceeding 80% at Jet Propulsion Laboratory employing receptor panels several square meters in area with total power on the order of 30 kW.[183] Receiver conversion efficiencies over 90% have been demonstrated in the laboratory as shown in Table 2.25.[183] These experiments have all used dipole receiving antenna devices coupled with galium arsenide Schottkey barrier diode rectifiers and appropriate coupling and filtering circuitry. Most of the experiments have coupled one dipole device to one diode. In order to maintain high RF absorption efficiency, the receiving antenna must space the dipoles such that the size of each dipole cell is 0.7 λ^2 to 0.8 λ^2. It is necessary to provide each diode with a power level near 1 watt to drive the diode hard enough to achieve reasonable efficiency. Moderate power (Amplitron or Magnetron) DC to microwave transmitter conversion efficiencies above 85% has also been achieved (see Table 2.26).[184]

Table 2.25

Microwave Rectennas (Reference 183)

Date	Contractor (Sponsor)	Diode Type	Rectenna Element Design	Efficiency
1964	Purdue U. (Raytheon)	Point Contact Si-W	Dipole-Balanced Bridge	60%
1965	Raytheon (Air Force RADC)	Point Contact Si-W	Beaded-String	60.5%
1968	Brown ( )	Schottky B. HPA Si-W	Dipole-Balanced Bridge	70%
1970	Raytheon, Ph.I (NASA MSFC)	Schottky B. HPA Si-W	Dipole-Balanced Bridge	75%
1972	Raytheon, Ph. II (NASA MSFC)	Schottky B. RAY GaAs-Pt	Dipole-Filter-Half Wave	80%
1975	Raytheon, Ph. III (NASA MSFC)	Schottky B. RAY GaAs-Pt	Dipole-Filter-Half Wave	87%
1976	Raytheon (NASA JPL)	Schottky B. RAY GaAs-Pt	Dipole-Filter-Half Wave	88%
1977	Raytheon (NASA-LeRC)	Schottky B. RAY GaAs-Pt	Dipole-Filter-Half Wave	92%

Table 2.26

DC-Microwave Converters (Reference 184)

	Unit Power	Voltage	Temperature	Efficiency
Klystrons	20-200 kW	40 kV	600~800 °K	80% +
Amplitron	5-20 kW	$\lesssim$ 20 kV	600~800 °K	85% +
Injection Locked Magnetron	5-20 kW	$\lesssim$ 20 kV	600~800 °K	85% +
Field Effect Transistors	1-20 W	10-20 V	370-500 °K	75%

Millimeter wave power transmission is now an established art concept in waveguides at relatively small powers. Beamed power transmission should be feasible using a new class of high frequency devices under development called gyrotrons (relativistic klystrons) and with solid state systems.[184] The gyrotron devices provide high power (hundreds of kilowatts to megawatts) at high efficiencies but require very high voltages[185] and may present substantial thermal control problems in the space environment due to the concentrated nature of waste heat sources.

Solid state systems are pushing higher and higher in frequencies. Efficient power production at 100 GHz and more has not yet been achieved, but there are solid state systems operating at low efficiency at frequencies of this order.[184]

At present, there are no millimeter wave analogues to microwave rectennas. A clear need exists for an efficient millimeter wave receiver, if this technology is to be used.

2.4.3.2 Lasers

Laser power transmission specifically for conversion into electricity at a receiver has been carried out only in laboratory-sized devices.[186,187] There are a variety of lasers exhibiting the potential for scaling to powers of interest for space power transmission. These fall into the categories of gasdynamic lasers (GDL) which are pumped by inverted vibrational state populations induced during rapid gasdynamic cooling of the lasant (e.g., CO_2 lasers);[188] electric discharge lasers (EDL) where inverted states are created by electron impact in the lasant (e.g., CO lasers);[189] direct optically pumped lasers (DOPL) where focused sunlight creates excited states which subsequently lase (C_3F_7I lasers);[190] indirect optically pumped lasers (IOPL) where radiation from a blackbody cavity heated by some external source, such as the sun or a nuclear reactor, is used to pump the lasant (e.g., CO or CO_2);[191] and nuclear fission lasers (NFL) where fission fragments pump the lasant (e.g., Ar-He or CO).[192] Numerous novel concepts have also been proposed, some of which will be discussed in Section 2.4.7.

Efficient receivers for converting laser radiation into electricity are in a primitive state of research. Several systems and device studies have been carried out which indicate potentially good conversion efficiencies (i.e., 50% and higher) for advanced concepts.[193-196] One of the experiments referenced above utilized a resonant absorption of CO_2 laser radiation in helium doped with SF_6 to achieve a high working fluid temperature in a glass-windowed Stirling engine with a linear alternator (i.e., a Beale-type Stirling engine). Approximately 10% conversion efficiencies were measured.[186] Efficiencies on the order of 40% have been measured for photovoltaic cell receivers at short wavelengths (0.6-0.85 μm).[197]

2.4.3.3 Waste Heat Radiators

Radiators are either active or passive systems. Passive radiators involve no circulation of coolants, relying entirely on heat transfer by conduction and/or internal radiation to an outer surface which radiates waste heat to space. This surface may be especially prepared to enhance its emission coefficient and to increase its radiating area, for example with fins. This technique is often used on the front and back of solar panels. With no area enhancement, such panels would rise to a temperature of approximately 60 $^{\circ}C$ before radiation losses balance the generation of waste heat (assuming a 15% photovoltaic cell and $\varepsilon = 0.85$).

Active radiators involve coolant circulation and permit the transfer of heat over much larger areas before the temperature falls too low for effective radiation. Heat pipe radiators rely on capillary forces and vapor diffusion to circulate the coolants in two phases. These devices circumvent the problem of moving parts (i.e., pumps) but are limited in the length of pipe over which heat can be transferred effectively. Large power systems will require large radiators extending over even greater distances, requiring pumped fluid systems or some novel concept or hybrid of existing concepts to transfer heat to the outer periphery of the radiator.

2.4.4 Limits to Present Technology

The practical limits to present technology required for beam power transmission can be phrased in terms of the transmitting and receiving components. As shown in Table 2.26, microwave transmitters have been tested with high efficiency (85% and higher) at moderate powers and somewhat lower efficiency at higher powers (i.e., klystrons at 20 to 200 kW and 80% or higher efficiency).[184] Projected state of the art advances in power-specific weight for high power CW microwave transmitters is shown in Figure 2.54.[180] From these data we conclude that present developments could lead to power-specific weights on the order of 1 kg/kw in the relatively near-term. These devices have the added feature that they operate at relatively high temperatures (i.e., 600 °K to 800 °K) so that waste heat radiation can be accomplished with relatively small areas.

Microwave receiving antennae (rectennas) have been constructed in small sizes primarily for eventual use as ground receiving stations. At least one experiment has been conducted with an airborne receiver designed with power-specific weight in mind.[198] However, there are no reliable data available to use as a benchmark for space-based receiver performance at this time.

Laser transmitter performance can be based on available lower power terrestrial technology and can be scaled to higher powers using the results of several recent studies performed for NASA. These studies have emphasized solar-powered space-based lasers,[188-191,199] although at least one has also considered nuclear powered lasers.[192] Closed cycle, continuous wave lasers at the 15 kW power level have been built and tested with one of the purposes being space power transmission.[200] Laser efficiencies on the order of 5% (laser power out/solar power received) are projected on the basis of these experiments, accompanied by power-specific weights of approximately 50 kg/kW at power levels of 1 Megawatt.[189] Again, these values cannot constitute a true benchmark because space qualification of high power lasers is still in a preliminary stage. There is good reason to believe, however, that advanced laser concepts will be able to do much better than these preliminary data would suggest, both in

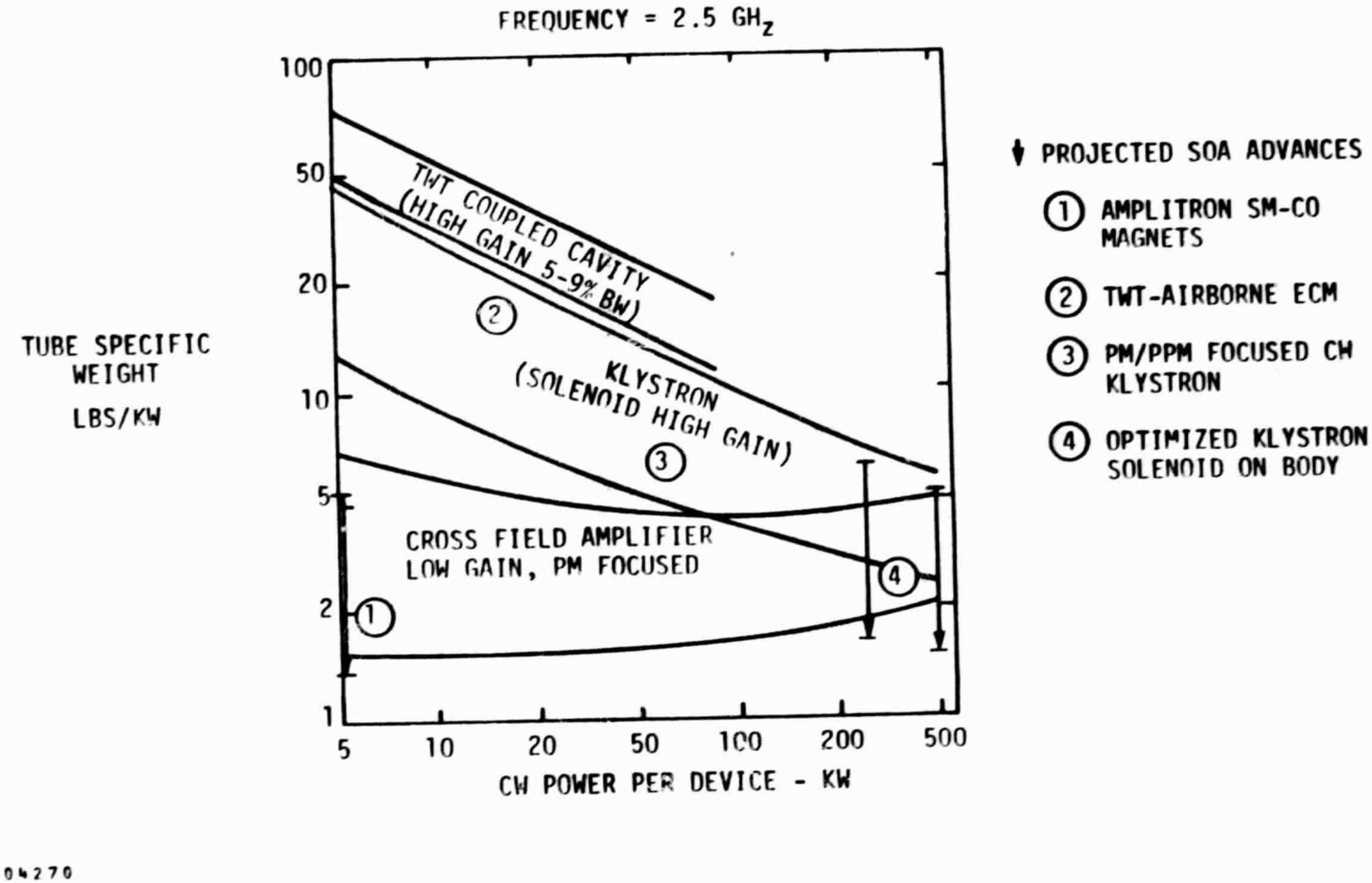

Figure 2.54. Weight Comparison of High Power CW Transmitters. (Reference 180)

terms of higher efficiency and lighter weights. Laser power receivers are also in the earliest stages of research and development, so that no reliable data exists for benchmarking their performance.

Waste heat radiators of the passive type typically operate at 50-300 °C and have power-specific weights on the order of 0.5 to 3 kg/kW(th).[201] Recent research suggests that the temperature range may be extended up to 400 °C with improved high emission coatings under development.[202] Passive radiators are used for dispersed power systems such as flat photovoltaics arrays where waste heat is generated at the location of the radiator and fin radiators are used for radioisotope heat sources. Active radiators, most notably heat pipes, have been designed and tested over a range of temperatures from 700 °K to 1700 °K, as shown in Figure 2.55.[180] The power-specific weight for heat pipe radiators depends strongly on temperature, as shown by the examples in Figure 2.56, where they are compared to a forced convection radiator.[180] The basic weight constraint for active radiators has been imposed by the need to armor the radiator against puncture by meteorites.[203] Because of the precipitous increase in man-made debris in low Earth orbit, an even greater probability exists for collision between the radiator and these artificial meteorites.[204] In higher Earth orbits, the meteorite danger may have been over-emphasized in the past; a re-examination of newer data appears to be in order. Also, novel active radiator concepts may help to circumvent or mitigate the need for armoring. A measure of armored radiator power-specific weights as a function of temperature is given in Figure 2.57. Any advanced concept projecting much lighter weights than these would be a good candidate for the Advanced Energetics Program.

2.4.5 Basis of Comparison

The appropriate criteria for comparing beam power transmission options are efficiency and power-specific weight. These numbers are mission-dependent, since placing the transmitter on the ground will produce quite different constraints than an orbiting transmitter. In this study all of the receivers are assumed to be in space. The energy per photon is

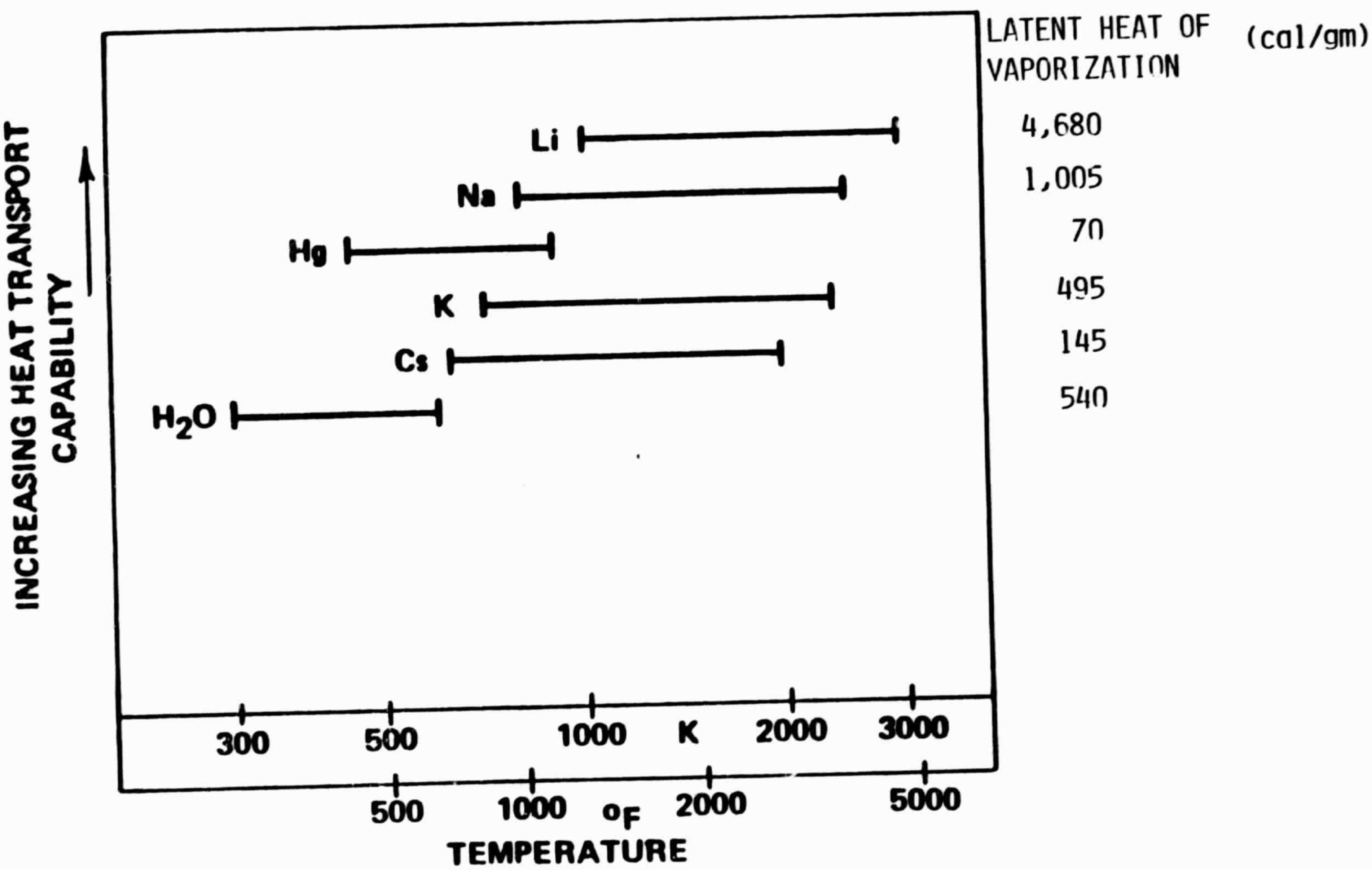

Figure 2.55. Heat Pipe Radiators (Reference 180)

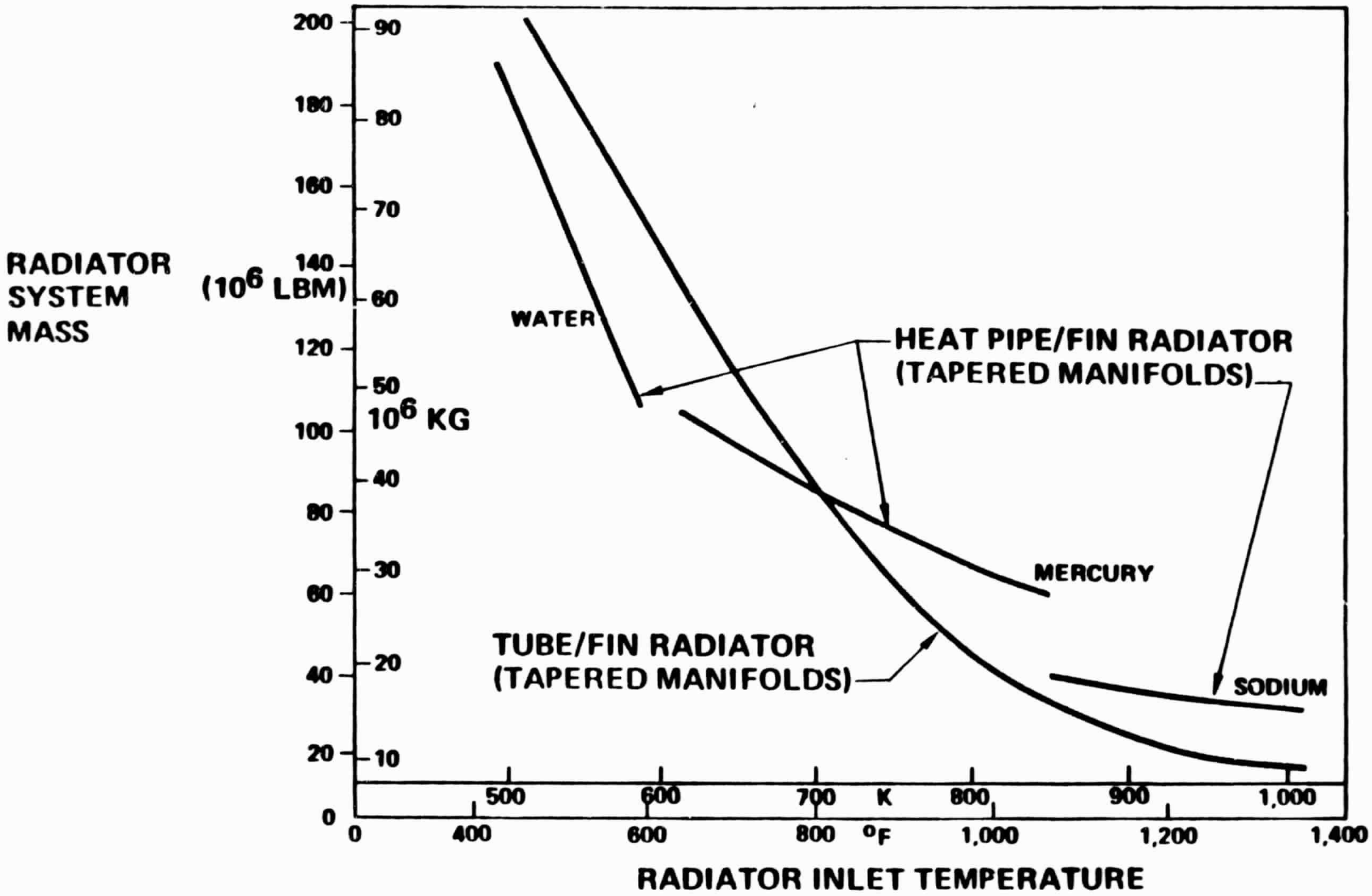

Figure 2.56. Heat Pipe and Tube Finned Radiators (10^{18} *GW* of radiated power: Reference 180).

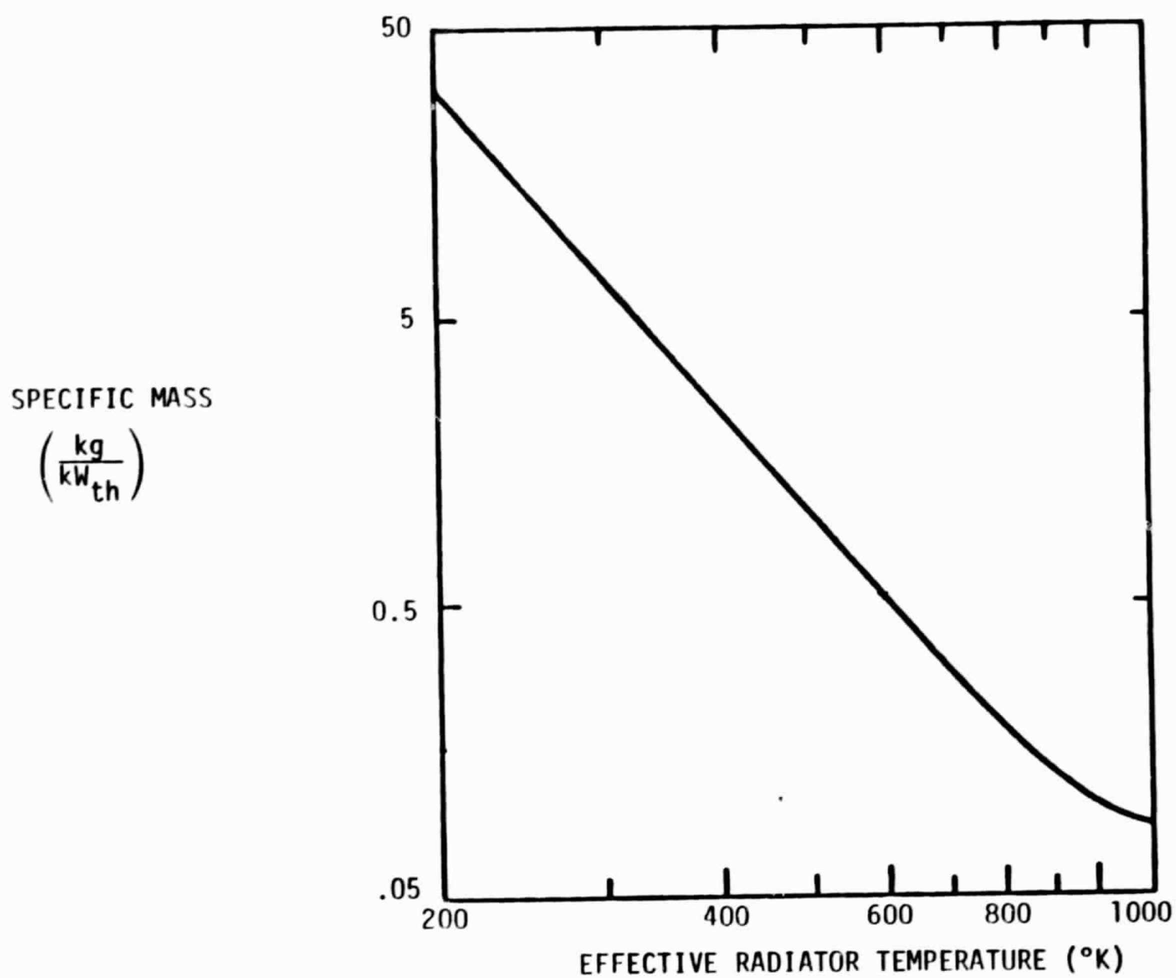

Figure 2.57. **Specific Radiator Mass** (Reference 201).

also a figure of merit, since this is related to the product of transmitter and receiver antenna diameters (see Figure 2.53) and also affects the range of receiver efficiencies available and the transmission efficiency in the case of ground-based transmitters.

Power-specific weight and, as a secondary figure of merit, the temperature are appropriate measures of waste heat radiator performance. As the temperature changes the types of radiator material will also change, as well as the area required for radiation of a given amount of power.

2.4.6 Applicability to Generic Missions

Studies and technology work done under DOE and NASA sponsorship on the solar power satellite technology program have demonstrated that energy beaming, in principle, can be efficient; a clear determination has not developed as to the desirability of the solar power satellite as a commercial energy system.(179-181) This discussion is aimed at potential applications and technology of power beaming to support space missions.

Space to Space. A number of studies have also considered the application of microwave space-to-space power beaming with the idea of a central power generation plant supplying power to spacecraft which did not include their own power supplies.(205) These studies have not yet indicated a clear advantage for this technique over simply providing power supplies for the spacecraft. Power beaming for space propulsion is still of some interest. The main application is in power beaming for propulsion systems traveling from low Earth orbit to geosynchronous orbit. The principle interest in power beaming stems from the problems attendant to carrying self-contained solar photovoltaic power supplies through the intense Van Allen radiation belts of Earth. Either RF or laser power beaming can alleviate this problem. A laser power beam may be converted directly to heat for heating a propellant. This technique has been the subject of several NASA studies and/or technology activities and will not be discussed further here.(206)

RF power beaming could be used to provide electric power to an electric propulsion system. The RF receiver is not likely to be less massive per unit area than a solar array, but could be more efficient and far less subject to radiation damage.

Space to Lunar Surface and Mars Surface. The eventual construction of manned bases or settlements in space has been widely discussed in futuristic literature and has been the subject of some NASA and university studies.[207] Potential locations for such settlements have included the lunar surface, Mars surface, and various locations in space. Space based facilities could most easily provide their own power. Facilities either on the lunar surface or on the Mars surface could utilize beamed power. This is particularly important on the lunar surface where the lunar night lasts approximately 2 Earth weeks and locally generated power seems practical only through nuclear options. The Mars day/night cycle is similar to that of Earth, but the use of beamed power there also may be of interest.

The feasibility of power beaming is dependent on a suitable location for the power beaming spacecraft. Fortunately, both the moon and Mars have such suitable locations. For the moon these are the lunar libration points, L1 for the side of the moon facing the earth, and L2 for the far side of the moon. For Mars the appropriate location is the Mars analog of geosynchronous orbit. These locations are shown in Figure 2.58. Both the lunar libration point L1 and the aerocentric orbit provide beaming ranges less than that from geosynchronous orbit to Earth, the latter having been considered for solar powered satellites.

Power Levels. The solar powered satellite studies dealt with power levels in the thousands of megawatts. It is not likely that early applications of space based power beaming would deal with such high power levels. Therefore, one must consider systems that can deal with substantially less power.

For a lunar surface base, three principal applications of power may be considered. The first is life support, lighting, and other accommodations for base personnel. These functions will consume roughly 5

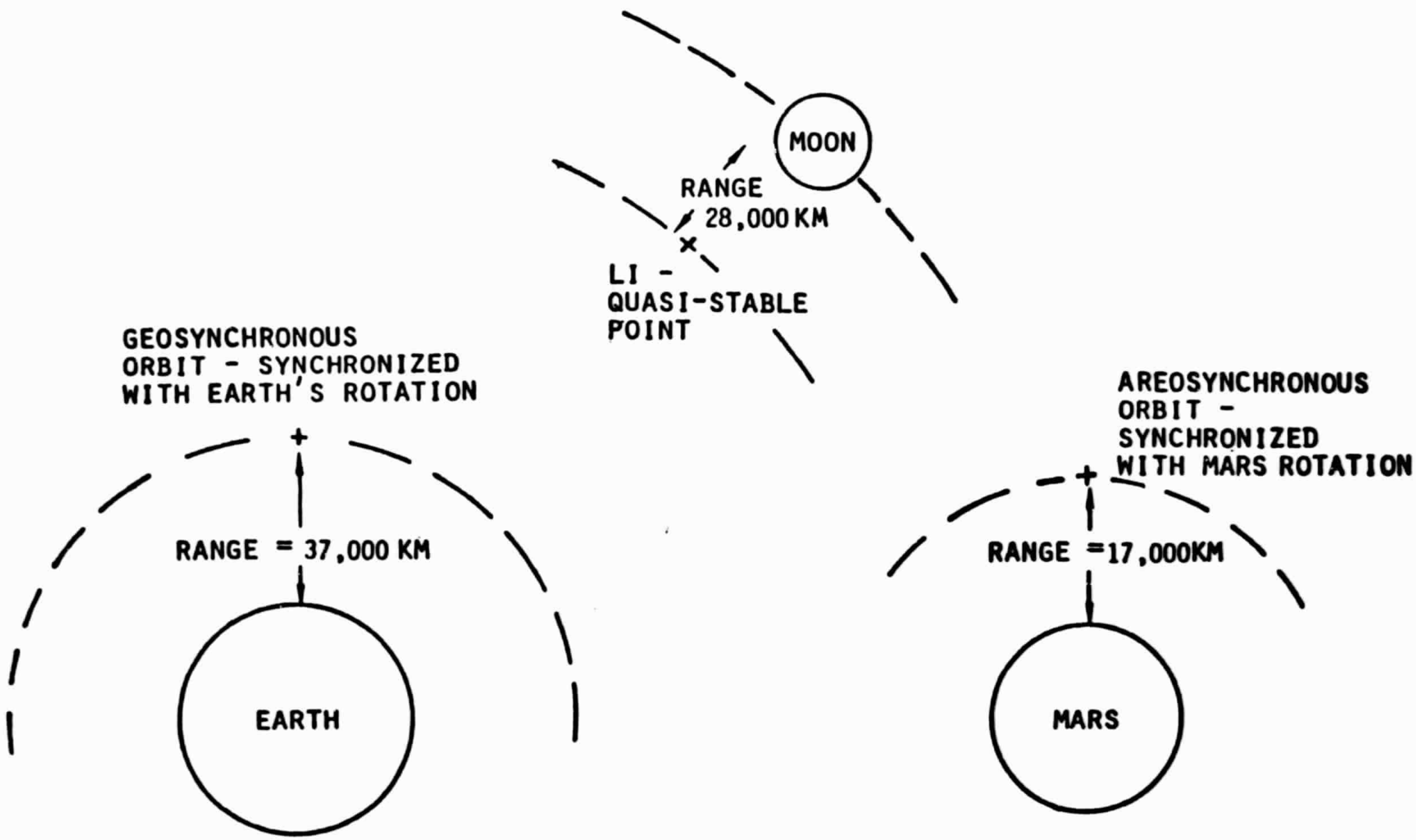

Figure 2.58. Power Beaming Locations

to 10 kilowatts per person. A second potential application is for agriculture. The lunar night is a long dark period, as stated above. The power requirement to sustain agriculture during nighttime periods may range from 5 to 20 kilowatts per person. A third potential power use is indigenous industry. Two likely products include aluminum and oxygen. Aluminum would have evident structural uses, and oxygen would be used primarily for propulsion.

The availability of lunar oxygen would allow a simple, single stage, cryogenic vehicle to shuttle back and forth between low earth orbit and the lunar surface. The vehicle would be fueled with enough hydrogen in low earth orbit for the round trip and enough oxygen simply to reach the lunar surface. Oxygen would be re-fueled on the moon. Such a vehicle would have a payload capability in each direction of 10 to 12 percent of the propellant load.

The production of oxygen will require roughly 20 kilowatt hours per kilogram. Aluminum will be a byproduct. Depending upon the feedstock, aluminum and oxygen may be produced in roughly equal mass quantities. Power levels on the lunar surface of a few tens of megawatts would allow shuttle trips every week or two between the Earth and the moon. A plausible power beaming system could produce its own mass in oxygen and aluminum in no more than a few weeks.

From these discussions it is reasonably clear that power levels in the range of 10 to 100 megawatts are of some interest. Either RF or laser beaming might provide the power in this range. A number of studies of laser power beaming have been conducted, and technology recommendations for laser power beaming have been made as a part of those studies.[182,199]

Need for Millimeter Wave. RF power beaming through the Earth's atmosphere is restricted to wavelengths on the order of 10 centimeters or longer because of the intense atmospheric absorption of shorter wavelengths. For space to space or space to lunar/Mars applications, however, much shorter wavelengths on the order of millimeters or less could be considered. These shorter wavelengths may permit effective power

beaming of a few tens of megawatts with RF techniques that may be more cost-effective than laser techniques.

Power Beaming Nomograph. Power beaming is amenable to fairly simple nomography to present the most significant interrelationships. Figure 2.59 presents such a nomograph for the lunar surface power beaming range of 28,000 kilometers. An example is shown.

A transmitter aperture between 200 and 300 meters was selected with a 2 mm wavelength. This provides a receiver aperture slightly greater than 500 meters to intercept over 95% of the power beam. It is desired to transmit 100 megawatts, resulting in a power density of approximately 5 kilowatts per meter^2 from the transmitter. If the power beaming efficiency is 50%, this results in a received power of 50 megawatts, and the receiver aperture and received power result in a received power density of approximately 100 milliwatts per square centimeter.

The nomograph is based upon a transmitter illumination taper of 10 db, which provides efficient power beaming with most of the radiated power contained within the main lobe of the power beam. The average to peak power density for the transmitter is approximately .4, and the average to peak level at the receiver is approximately .21. These average to peak ratios were used in plotting the received and transmitted power densities, both of which are peak values.

Earlier studies of power beaming have suggested feasible transmitter intensities of 4 to 5 kilowatts per square meter for solid state systems, and a little over 20 for vacuum tube systems employing magnetrons, klystrons, or, perhaps more appropriate for millimeter wave systems, gyrotrons.(184) A received power density of 100 milliwatts per square centimeter appears to be safe for the applications considered here, particularly given the very limited penetration power of millimeter waves.

The illustration shown on the nomograph indicates the applicability of millimeter wave systems to power blocks in the range of 100 megawatts or less.

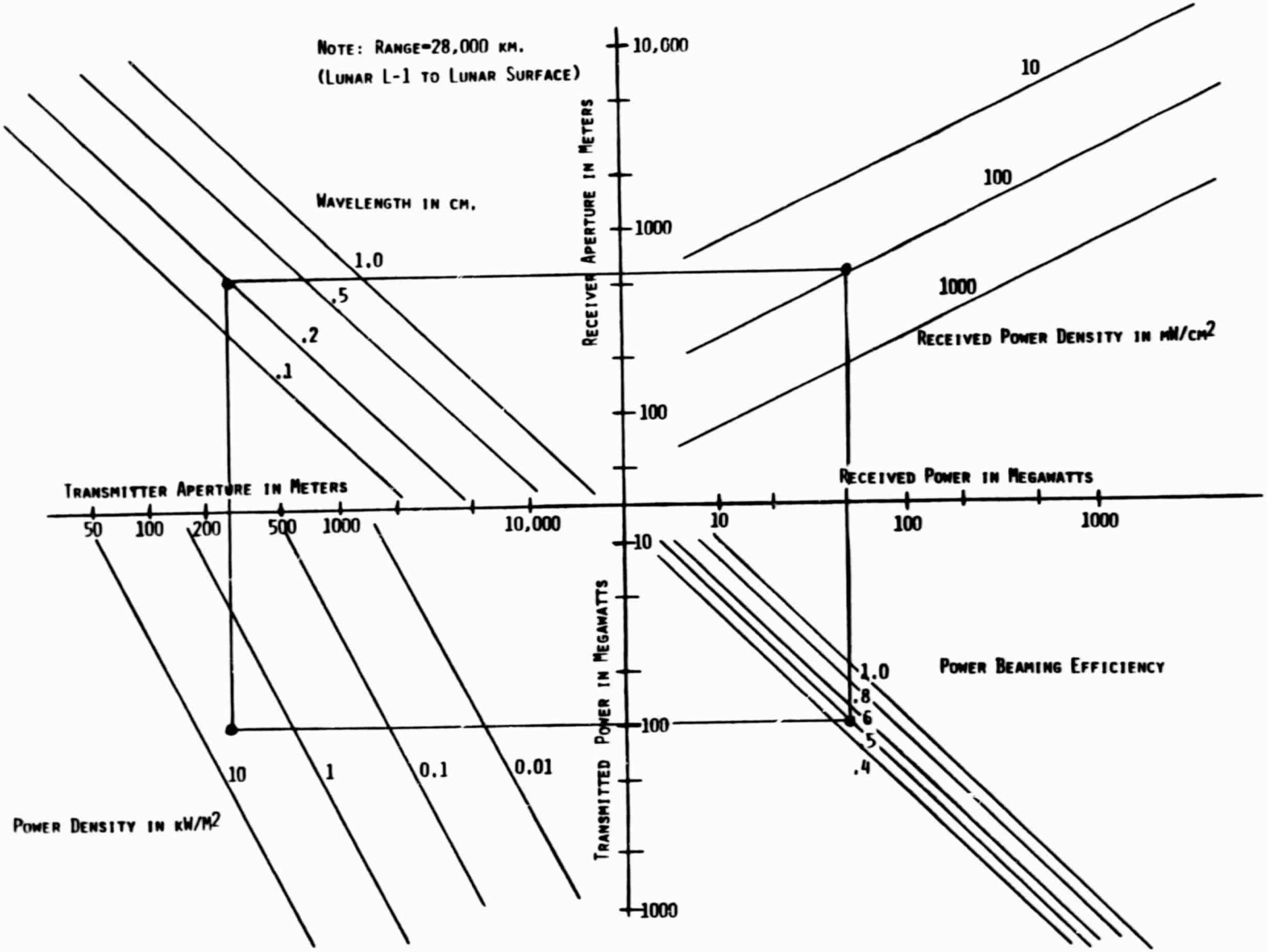

Figure 2.59. Millimeter Wave Power Beaming.

Applicability of waste heat radiators is virtually mission independent, varying instead just with the temperature and total amount of waste heat power which must be rejected. The only conventional constraints which must be recognized are that radiators should face away from the sun if they operate at relatively low temperatures, and in low Earth orbit the re-radiation from the Earth must be considered in determining the true heat rejection rate from the radiator.

2.4.7 Advanced Technology Assessment

2.4.7.1 Microwave and Millimeter Phased Arrays

Substantial performance advances may be available in microwave beam power transmission through the use of solid state devices. A recent review of the devices[184] suggests that antenna-mounted gallium arsenide field effect transistors (FETs) acting as the basic dc-rf converter could offer smaller receiving antenna areas for transmitter costs similar to those characterizing the klystron approach. However, the biggest advantage of the solid state device is a much lower failure rate (a factor of 100) than vacuum tube devices.[179] The disadvantage inherent in this approach is that the solid state devices are constrained to operate at temperatures like 100 °C. The key question is whether or not an 80% conversion efficiency can be attained. The status of relevant solid state technology is illustrated in Figure 2.60[184] where it can be seen that there is a large gap between achieved (67%) and desired (80-85%) conversion efficiency. Even if this level is achieved, the power per unit will probably be limited to 1 to 10 watts, implying that many units are required, even for modest powers. An evaluation demonstration program on solid state rf transmitters is currently underway at RCA Laboratories[208] under NASA funding. The results of these initial experiments should be reviewed at their completion to determine the advantages of further exploration for the Advanced Energetics Program.

Millimeter wave power generation is of significant interest for various earth based applications. Accordingly, technology developments are taking place both with gyrotron devices (relativistic klystrons) and solid

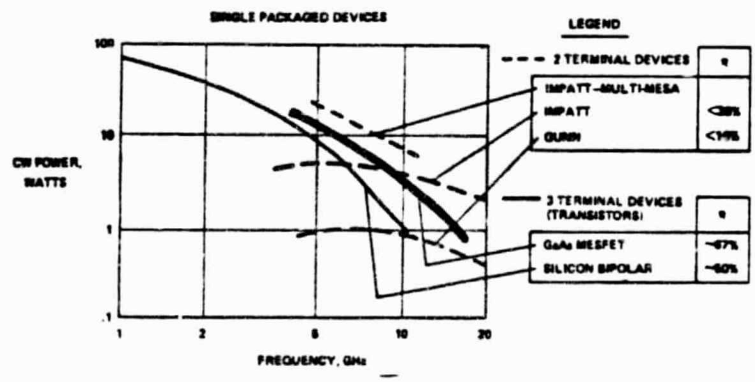

Figure 2.60. Solid State CW Power Status.
(Reference 184)

state systems. Radiation of the RF power at these frequencies will most likely be effectively accomplished with slotted waveguide radiators. The principle issues at millimeter wave frequencies include multifactor problems and the high dimensional precision and stability required to maintain effective radiation efficiency at these short wavelengths.

The nomographed example in Figure 2.59 considered a 250 meter transmitter aperture with a 2 mm wavelength. The transmitter diameter is 125,000 wavelengths. This may be compared to a transmitter d/λ ratio for the solar power satellite studies on the order of 10,000. The latter figure is considered as quite challenging. By comparison, optical systems deal in d/λ ratios of 1 million and greater.

For a millimeter wave system, the power within each wavelength unit receiver cell may be, at most, a few milliwatts without additional focusing. Consequently, the receiving device might have to combine hundreds of unit cells per diode. A suggested technique is the use of slotted wave guide or slotted cavity resonators to absorb the RF radiation and provide the power to the rectification equipment.

2.4.7.2 Laser Power Transmission

TRANSMITTERS

Virtually any high power, space-based laser system must be considered an advanced technology. The key problems are to determine the best lasers for each type of application according to wavelength, power-specific weight, scalability to high powers, lifetime, and reliability as a cw source. Critical technology problems include the development of lightweight radiators to reject waste heat from the laser cavity (and other power equipment), high intensity cw laser optics, lightweight solar concentrators in the case of solar-powered lasers, pulsed high voltage systems for space in the case of EDLs, and long lifetime lasants for cw closed cycle operation.

Gas lasers or Free Electron Lasers (FEL) are virtually the only varieties capable of being scaled to high powers because waste heat can easily be transferred from the lasant at a moderate to high temperature. In contrast, solid or liquid laser systems do not scale well to high power cw operation because heat cannot be transferred easily from the lasant in these two cases. Table 2.27 summarizes the basic types of high power lasers and some of their features. This list is illustrative only since there are many lasants, for example, that could be used with each laser concept. Initial scaling exercises suggest that the GDL is far too heavy compared to EDLs and to the other concepts listed in Table 2.27 to be considered any further.(209) Its basic disadvantage is inherent in the concept of creating inverted populations with thermal energy (i.e., a heated gaseous lasant). The other schemes use much more selective inversion techniques where the pump energy is made to excite just a few states instead of all of them. As a result, EDLs, IOPL, etc. have much less reject heat (i.e., higher efficiencies) than the GDL.

There are large differences in the level of development of the remaining laser candidates. EDLs are a well established laser technology at moderate power levels. A closed cycle, 15 kW cw EDL has been built and tested at NASA-Lewis Research Center.(200) In contrast, direct optically pumped lasers and indirect optically pumped lasers are in a very embryonic stage since gain measurements are about the only test which has been carried out. Proof-of-concept experiments must be carried out for DOPLs and IOPLs before their potential can be assessed properly. The FELs have been operated as oscillators, but their behavior as an efficient device is still in debate. Several FEL proof-of-concepts are presently underway.(210) The results of those experiments should be critical in establishing the merit of the FEL concept.

Clearly, new ideas in this area are required in order to make high power laser concepts fit the very special requirements of continuous operation in space. The EDL makes no special accommodations in this respect, operating very much as it would on the ground. Electricity is produced first for pumping the lasant. In some cases the lasant is kept

Table 2.27
Solar Driven Lasers Delivering 1 MW(e) Output at the Ground
(Reference 209)

Type	Lasant	λ	η_T	η_L*	η_{TOT}+	Mass
EDL	Supersonic CO	~ 5μ	57%	5.7%	3%	36×10^3 kg
DOPL	Subsonic CF_3I	1.315μ	95% (est)	0.5%	0.4%	63×10^3 kg
IOPL	Subsonic CO/CO_2	9.114μ	83%	15.4%	10%	36×10^3 kg
FEL	Relativistic Electron Beam	Tunable $\lambda > 2.5\mu$	95% (est)	9.5%	7%	14×10^3 kg

* 25% Solar to Electric Thermal Conversion Cycle Assumed

\+ $\eta_{TOT} = 0.8\ \eta_T \eta_L$, η_T = atmospheric transmission, η_L = laser transmitter efficiency.

Ground-based receiver efficiency assumed to be 80%.

cold to enhance lasing efficiency. In the case of some excimer EDLs the lasant may be warm or hot, which would make waste heat rejection more efficient.

In contrast, the DOPL and IOPL concepts are designed to be lightweight for the power they produce. The direct optically pumped lasers typically have a very narrow laser absorption band in the visible (i.e., within the solar spectrum). This feature generally implies that an enormous amount of light outside this band will also be absorbed as waste heat, necessitating larger radiators. However, if the light is filtered first so that only the laser absorption band radiation spectrum from the sun is focused on the lasant, then the unused radiation is allowed to pass through the collector, vastly reducing the size of the lasant radiator (see Figure 2.61).

The IOPL utilizes a unique concept of energy recycling whereby the lasant absorbs a narrow band from the blackbody cavity radiation spectrum. This "notched" spectrum is continuously refilled by radiation re-emitted from the cavity walls. Thus, energy recycling permits the use of broad band radiation to excite the lasant in a very narrow absorption band. The main loss in the IOPL is the heat absorbed by the transparent tubes which carry the lasant through the blackbody cavity (see Figure 2.62).

The FEL, on the other hand, has no lasant at all. Instead, an oscillating beam of relativistic electrons rides in phase with a growing light pulse whose frequency is determined by the electron energy and by the oscillation induced in the electron beam by a series of alternating polarity magnets stationed along the length of the laser cavity (see Figure 2.63). Waste energy is generated in the electron beam as the light pulse grows. This waste energy manifests itself as a dispersion of electrons in phase space away from a monoenergetic distribution. Recovery to a monoenergetic, in-phase distribution or recovery of the total remaining electron energy (in the case of single pass devices) is the key to developing an efficient FEL. The CATALAC FEL concept, developed at Los Alamos[211] and shown schematically in Figure 2.64, is based on a single pass FEL in which the spent electrons are recycled through the electron

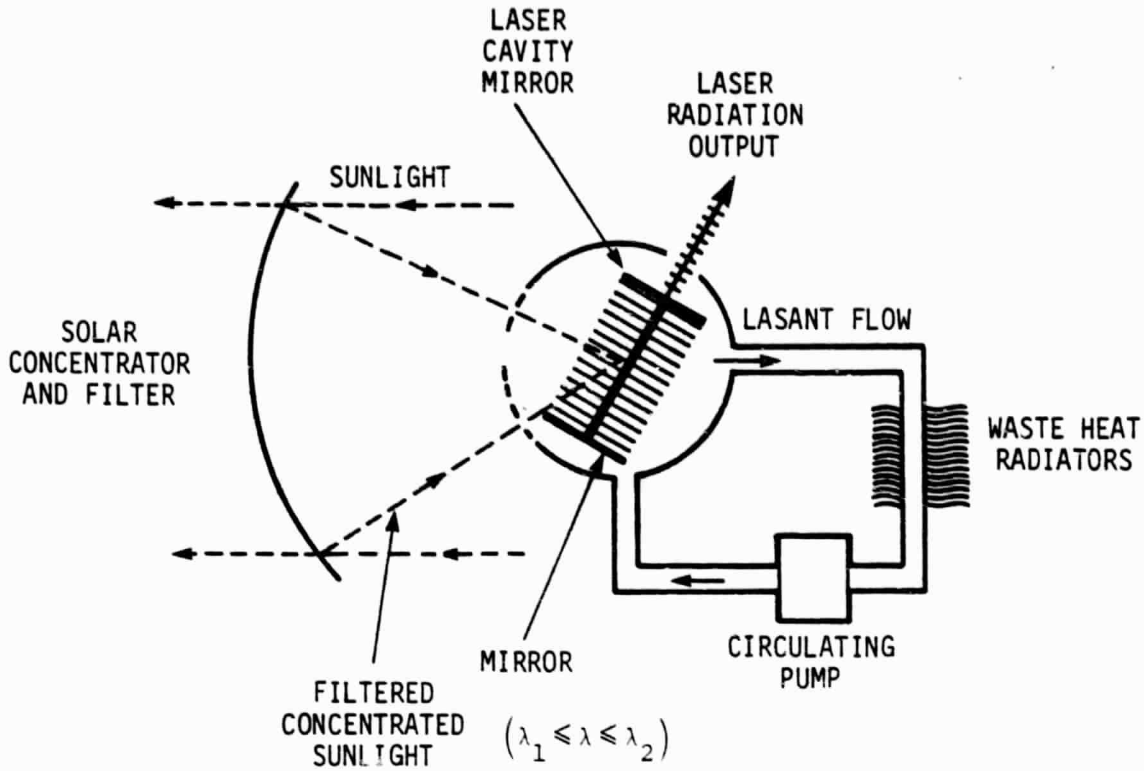

Figure 2.61. Direct Optically Pumped Laser (DOPL) using a filter/reflector to concentrate the sunlight and reduce waste heat rejection.

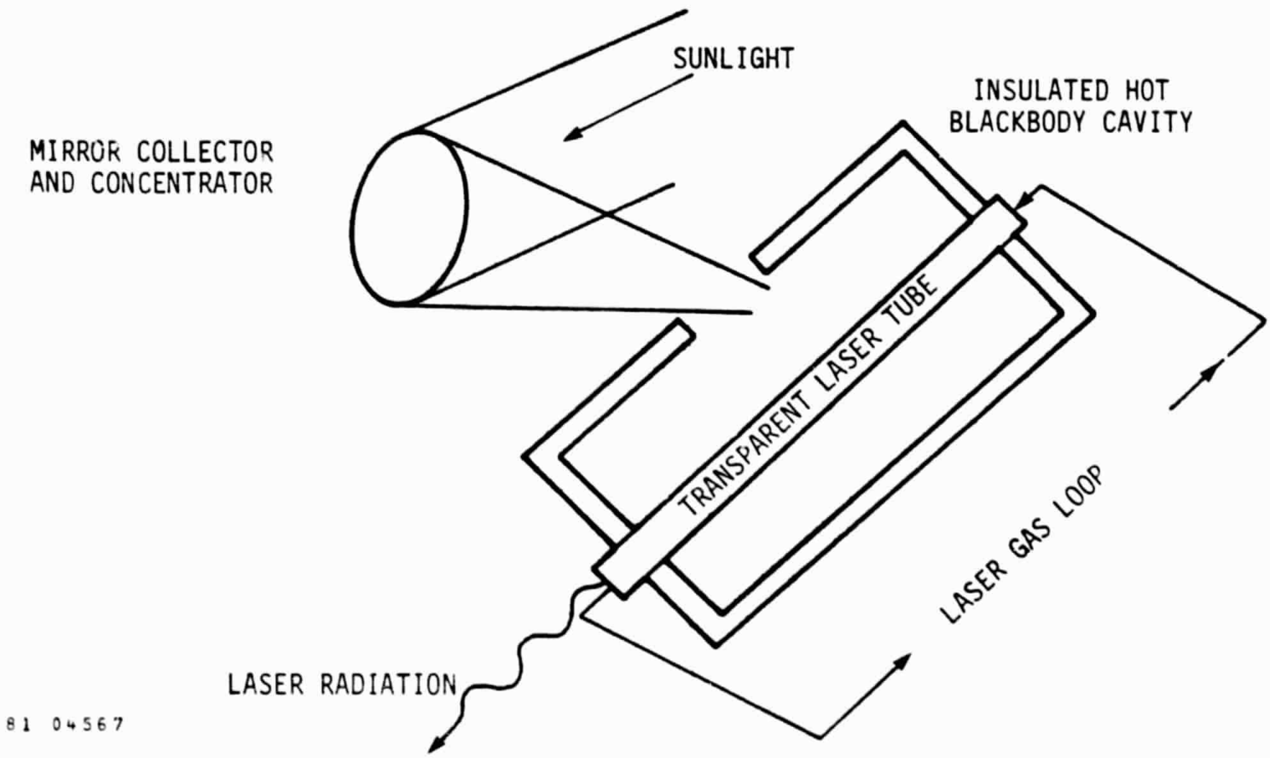

Figure 2.62. Indirect Optically Pumped Laser (IOPL) using Blackbody radiation to pump the lasant and recycle the unabsorbed energy to increase laser efficiency. (Reference 191)

accelerator to help build up the RF acceleration fields. In theory, the old electron bunches emerge from the accelerator having given up most of their remaining energy. Other concepts for multiple pass devices have been proposed which intend to reconstitute the monoenergetic character of the electrons over a series of passes through the storage magnets. Each of these ideas (single or multiple pass) has some controversial aspects to it and will need more careful analysis and testing to assess its potential. The FEL does have one overriding advantage: If it works as predicted, the electrical energy needed to drive the accelerator can be supplied by klystrons, which can reject their waste heat at quite high temperatures. Also, FELs appear to scale quite naturally to high powers. Beam intensity and electron accelerator emittance pose the next highest priority problems when it comes to actually making such devices work at high power.

Reversible chemical lasers may also exist which would suit them for high power cw operation in space. For example, a closed cycle HF laser system can be visualized in which the laser beam is produced by the chemical reaction between hydrogen and fluorine, which are regenerated by electrolysis. Because of the inherent storage capability possible with the H and F reactants, high rates of power transmission could be achieved for relatively short periods when needed, e.g., power beaming to users in orbit shadow with long regeneration periods. The power supply weight could thus be minimized; while the laser would have to be sized for maximum power rate, a chemical laser should have very favorable power-to-weight characteristics. Also, as compared to CO_2 laser beaming, the shorter wavelength HF laser will have smaller and lighter optics and receivers.

HF can be electrolyzed using solid polymer electrolytes (SPEs) in which porous fluorocarbon films (e.g., Teflon) are impregnated with the HF electrolyte. SPE units have been developed for water electrolysis and are capable of high efficiency, e.g., ~90%. The HF electrolyzer should have a relatively low specific mass, on the order of 1 Kg/kW(e). For power beaming systems with low duty cycles (e.g., on the order of 1%), the power supply and electrolyzer weight for the regeneration of the H and F reactants would be negligible.

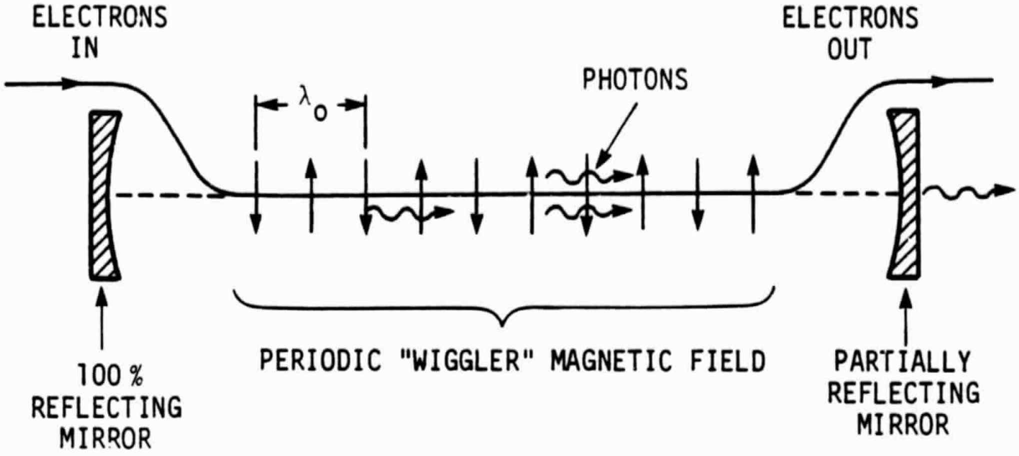

Figure 2.63 Free Electron Laser - Schematic of Cavity Operation showing interaction of photons with relativistic electrons in periodic magnetic field.

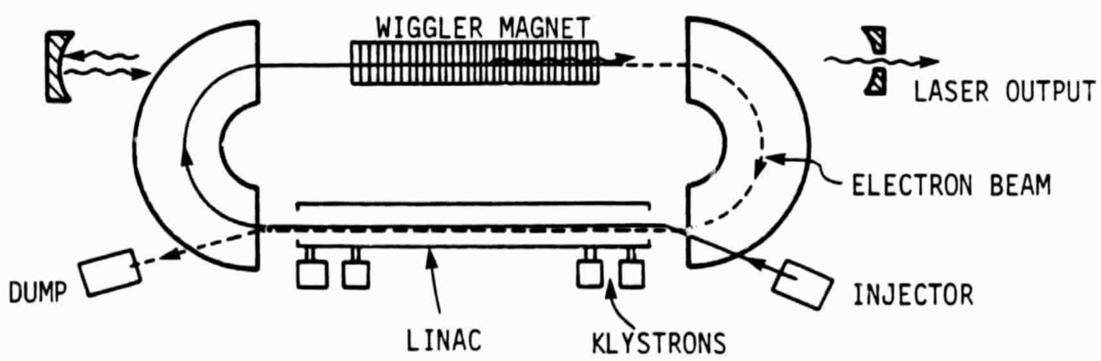

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Figure 2.64. The CATALAC Free Electron Laser Concept (Adapted from Reference 211)illustrating spent electron energy recovery in the Linac accelerator.

RECEIVERS

Numerous receiver concepts have been proposed for converting laser radiation into electricity. Direct conversion concepts (no moving parts) rely on the resonance between the incident laser photon energy and electronic excitation within the receiver. These devices are indicated in Table 2.28 as photovoltaics and optical diodes or microrectennas.[194] Thermal conversion concepts can also utilize resonant absorption with the intermediate development of thermal energy which, in turn, drives a heat engine (see thermal dynamic cycles and thermionics in Section 2.2). In this application, resonance absorption allows very high temperatures to be developed in the receiver without serious re-radiation losses.

Photovoltaic cell conversion of laser radiation can be very efficient if the laser wavelength is slightly shorter than the wavelength equivalent of the cell band gap energy. This insures that each photon absorbed results in a conduction electron with virtually no excess thermal energy. However, a certain fraction of photons absorbed produce no conduction electrons, and these contribute the main losses in the receiver. Estimates of efficiency, as shown in Table 2.28, range from 30% at present to values as high as 45%. Efficiencies much larger than 45 to 50% appear highly improbable because of recombination and diffusive losses of conduction electrons in the applicable semiconductor materials. The power is limited mostly by the array or receiver size. If the laser radiation is concentrated, then the higher intensities will improve the receiver performance up to similar limits. The disadvantage of this approach is that the waste heat must be rejected at relatively low temperatures. Nevertheless, this problem can be balanced off against the demonstrable reliability of photovoltaic cells. In effect, this is a fail-safe option with a relatively well-developed technology. Lacking a flight-proven laser receiver, photovoltaic cells come as close as one could hope to providing a benchmark for this technology.

By contrast, only the most elementary experiments have been performed to test the concept of microrectenna designed to convert monochromatic radiation to electricity.[212] The basic concept is

Table 2.28

Projections for Laser Energy Conversion
in 1978-80 and 1980-90
(Reference 194)

	1978-1980	1981-1990
1. Photovoltaics	AMOS ($GaAs_{1-x}P_x$) 30% efficiency megawatt power levels wavelengths below 1 μm	AMOS 45% efficiency megawatt power levels lower cost, λ < 1 μm
2. Heat engines	Piston engine: Otto or diesel cycles 50% efficiency 1-10 kW wavelengths near 10.6 μm	Turbine 75% efficiency megawatt power levels wavelengths near 5 μm
3. Thermionics	TELEC 40% efficiency 1-10 kW wavelengths near 10.6 μm	TELEC 50% efficiency megawatt power levels wavelengths near 5 or 10 μm
4. Photochemical cells	Photoassisted dissociation of water 15% efficiency wavelengths near 0.4 μm	Photoassisted dissociation of water 30% efficiency wavelengths near 0.6 μm
5. Optical diodes	Evaporated junction arrays not ready to convert power	Evaporated junction arrays 50% efficiency megawatt power levels respond to wavelengths from UV to over 10 μm

illustrated in Figure 2.65 which shows a metal-oxide-metal junction being irradiated at optical frequency ω. Below the schematic are the three principal phenomena contributing to the development of voltage in this junction. These are due to tunneling caused by the incident photon energy and the thermal energy of the metals, each modulated at the frequency of the incoming light. This latter effect is the primary mode of operation for microrectenna: The oxide layer is designed to have dimensions on the order of the laser wavelength so that the oxide layer will be polarized in phase with the incoming radiation. The natural difference in conduction band energies of the two different metals insures that the induced voltages will be rectified to produce a pulsed DC output. The oxide forms a barrier to prevent lower energy electrons (e.g., thermal electrons) from swamping the optically induced voltage. The experiments have demonstrated conversion efficiencies on the order of 5%.(194) Theoretical efficiencies in excess of 50% and as high as 80% have been projected for this approach.(199) The key problems are the manufacture of submicron junctions within acceptable tolerances, the electrical control network associated with these junctions, and demonstration of higher efficiencies at the higher intensities needed to make the junction work well. In this regard, microrectenna would probably work best with rapidly pulsed laser radiation where the average power is delivered in units of very high peak power (e.g., estimates for peak intensities are approximately Gigawatts/m^2).(199)

Thermal conversion concepts include devices such as the laser heat engine and the TELEC. Actually, there are three classes of laser engines, as shown in Figure 2.66. Types I and II are heat engines, while the third involves conversion of laser radiation to vibrational energy and, thence, directly to work from an expanding gas without an intermediate thermal stage.(194) This last concept (called the photon engine), while theoretically feasible, encounters too many losses in gas circulation to make a practicable device. The Type I heat engine operates just as a solar "boiler" would, since it is not dependent on the monochromatic aspects of the incident radiation.

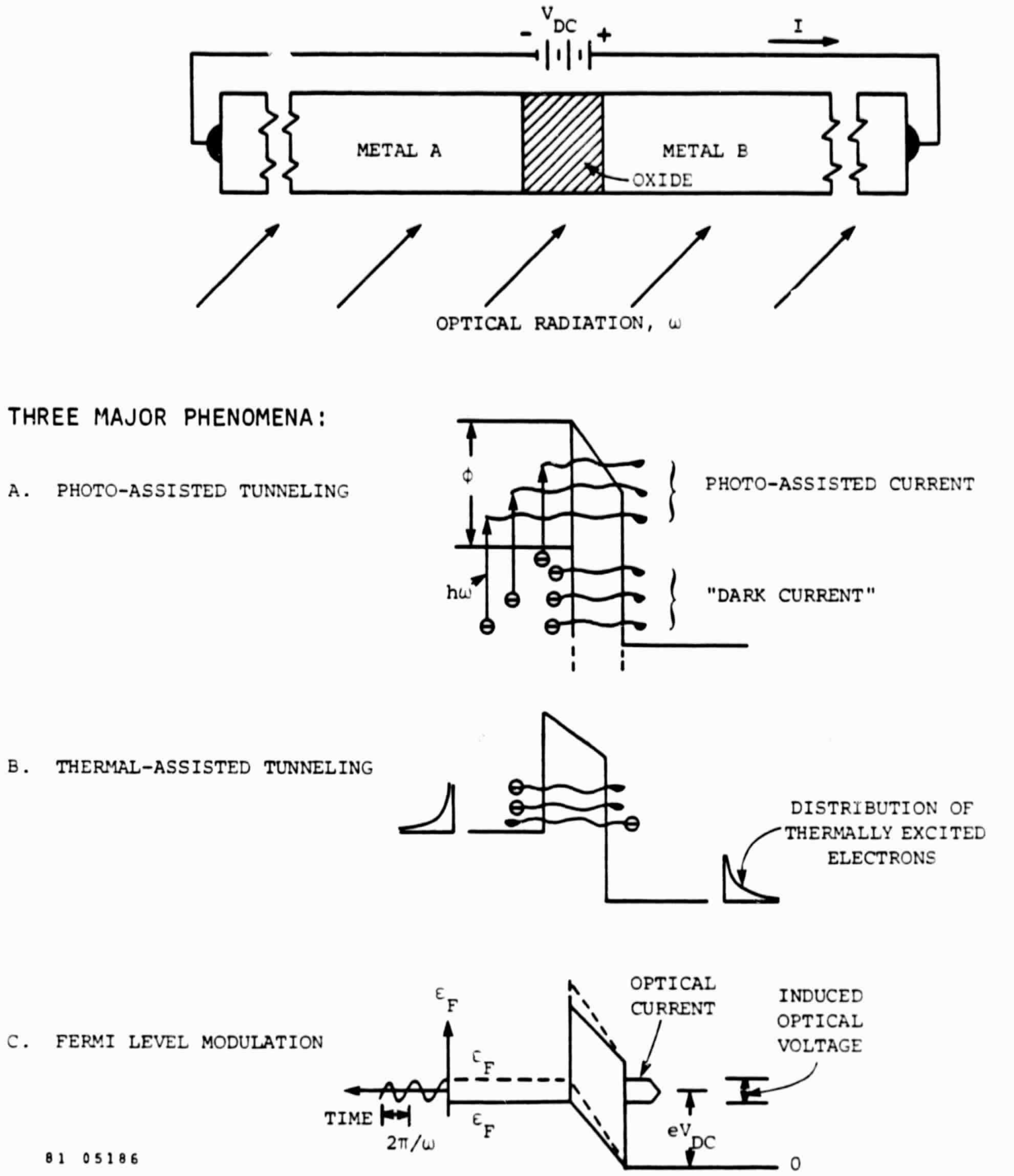


Figure 2.65. Currents in Metal-Barrier-Metal Junctions - A schematic representation of the three major phenomena which result when a metal-barrier-metal junction is irradiated (Reference 212).

A. Photo-assisted Tunneling: The "dark current" is due to the electrons that are not excited. For simplicity, the electron excitation in only one metal is shown.

B. Thermal-assisted Tunneling: The Fermi tails are only of the order of kT.

C. Fermi Level Modulation: Modulation is around the biasing point V_{DC}. The potential barrier is simplified by a trapezoidal barrier.

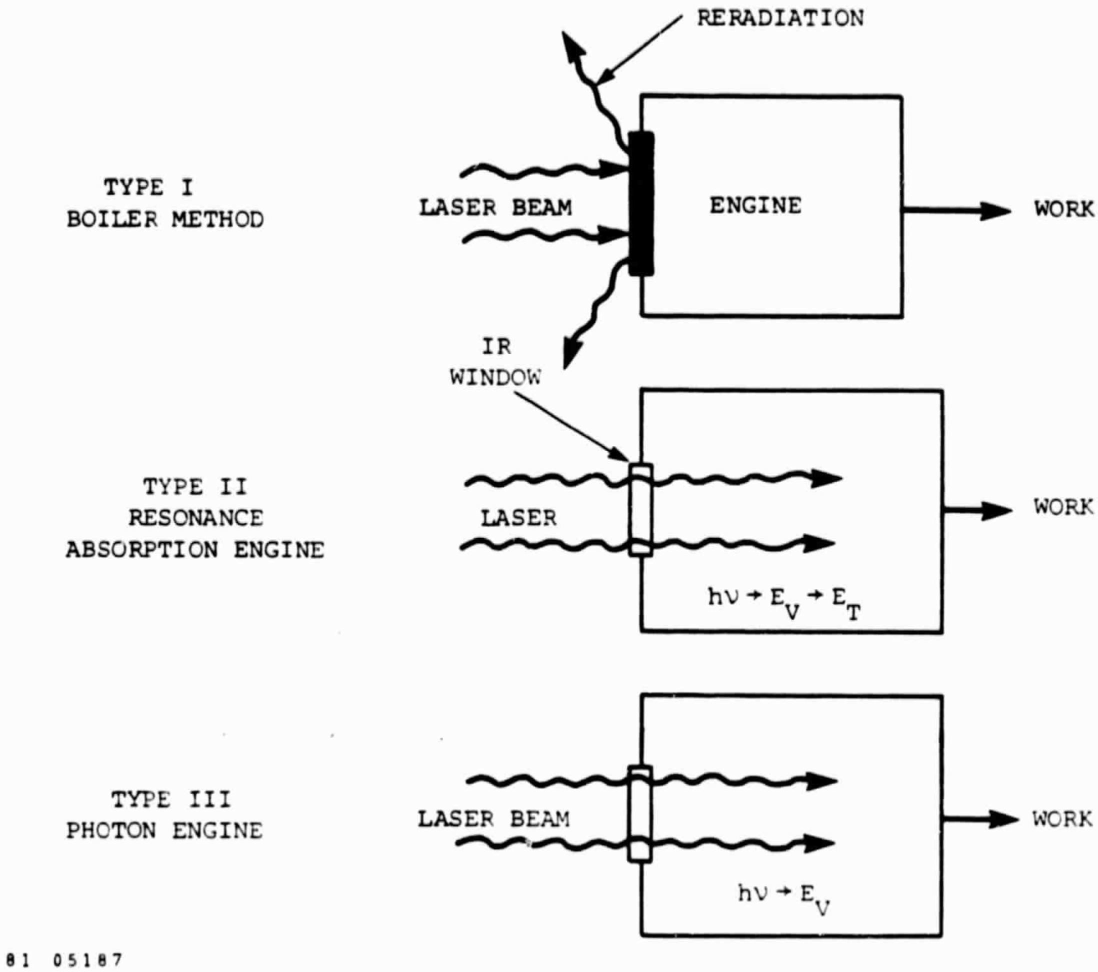


Figure 2.66. Three Classes of Laser Engines (Reference 194).

The Type II device, a resonant absorption heat engine, capitalizes on the thermodynamic potential of the laser radiation by absorbing the radiation in vibrational transitions, which are well above the thermal excitation level of the background gas. As a result, if a noble gas such as helium is used which rapidly deactivates the excited states in the absorber (e.g., SF_6 or CO), the background gas temperature will be heated (indicated in Figure 2.66 by the transition $E_V \rightarrow E_T$). Helium has the additional advantage of not radiating very well until its temperature rises to 10,000 $^{\circ}$K or higher because it has no vibrational states. Thus, working fluid temperatures on the order of 3,000 $^{\circ}$K should be quite feasible using this technique, with very small re-radiation losses. The result is the potential for very high thermal cycle efficiencies. A recent study of resonant heat engines indicates that only reciprocating engines utilizing Otto or Diesel cycles (or perhaps the high temperature expanders discussed in Section 2.2) can accept such high temperatures.[193] Initial experiments on a Stirling cycle resonant heat engine have been carried out. However, the conclusions were that the Stirling cycle approach would be limited to cycle efficiencies on the order of 30 to 40% without a substantial materials program which would still have an uncertain eventual payoff. The Diesel/Otto cycle or high temperature expander options offer immediate higher temperature capabilities with present technology, leading to efficiencies exceeding 50%. Experiments on these concepts need to be performed, with attention also to testing the effectiveness of the gaseous absorber and the transparent window required in the engine cylinder or receiver.

The TELEC represents a second class of direct conversion thermal heat engine based on thermionic converter principles.[213] In this concept, laser radiation is absorbed directly by an alkali metal vapor under high pressure. The dimer states of the alkali (e.g., Cs_2, Cs_3....) provide the appropriate asorption bands in the infrared. As the vapor heats it reaches a state of partial ionization, at which point absorption may also occur by inverse bremsstrahlung. The resulting plasma is electrically conducting and has an elevated, non-equilibrium electron temperature which is well suited for a geometric version of thermionic conversion. That is, one of

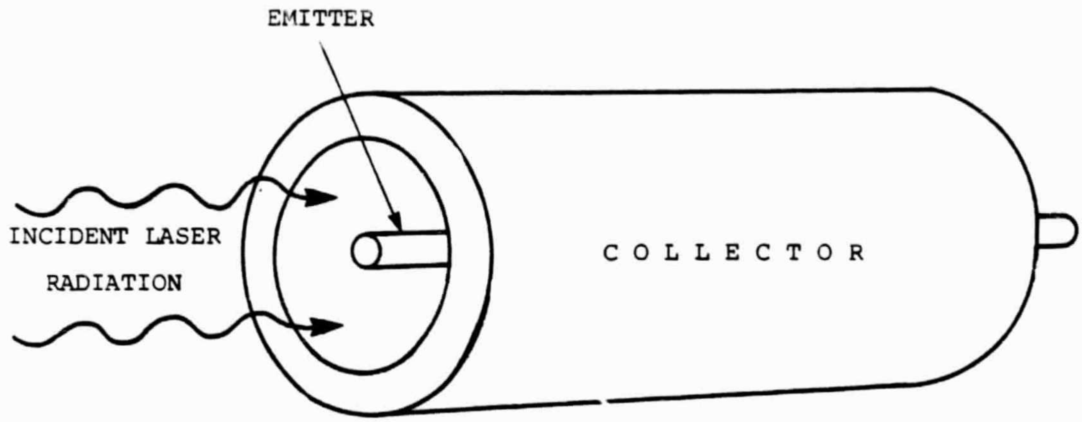
the electrodes presents a very small area to the plasma and the other a very large area. The larger area collects more electrons and, hence, becomes the negative electrode, developing a potential difference relative to the small area electrode. The larger electrode is cooled to prevent backward thermal emission of electrons. Two possible configurations are shown in Figure 2.67.

Initially, laser heating experiments have been conducted with the TELEC demonstrating a very low efficiency (i.e., 0.1%).[187] Projected efficiencies of 50% have been estimated. A preliminary review of these experiments and the theory is warranted to determine the reasons for such a large discrepancy and to more accurately assess the actual potential for this class of devices.

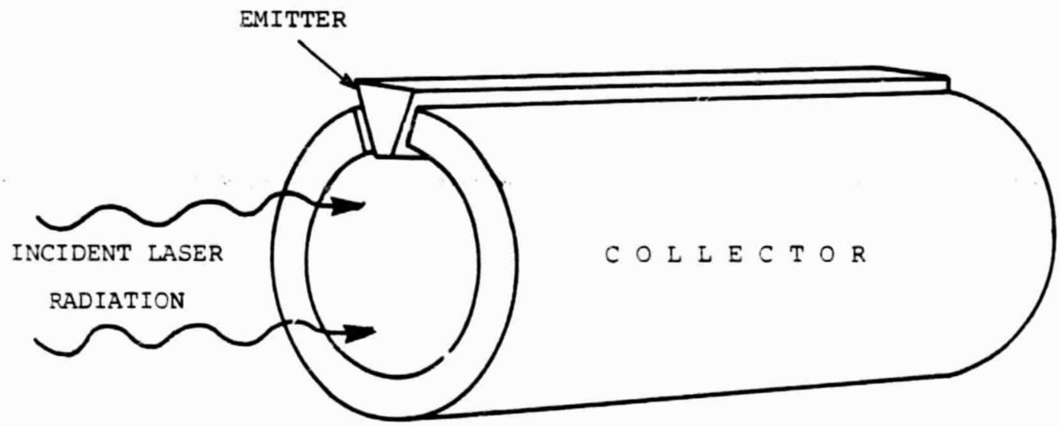
2.4.7.3 Waste Heat Radiators

Heat pipes are currently one of the most attractive waste heat radiators for higher power systems. Advances in this technology are required if higher powers are to be achieved in space. Higher temperature heat pipes would help to reduce radiator weight. Also, as radiator sizes increase, longer heat pipes or combinations of heat pipes and forced convection radiators will be needed. Considering the limit to present heat pipes to be approximately 3 meters, this would span a radiator with characteristic area of 56 m^2 (counting both sides of a circular area). At a radiator temperature of 600 ^{o}K, approximately 400 kW of waste heat can be rejected. With a 25% efficient thermal cycle, this radiator could accommodate a power system delivering 130 kW of net electric power.

High temperature heat pipe radiators (i.e., 775 ^{o}K) are being investigated for space nuclear power plants at Los Alamos.[214] These use potassium and are fabricated of titanium. By comparison to the example given above, these high temperature heat pipes would be capable of reducing the radiator area by 65%; alternatively, the net electric power output which could be accommodated could be raised to 380 kW. Fabrication of these heat pipes and subsequent reliability still present substantial technical challenges.



(a) Emitter In Beam



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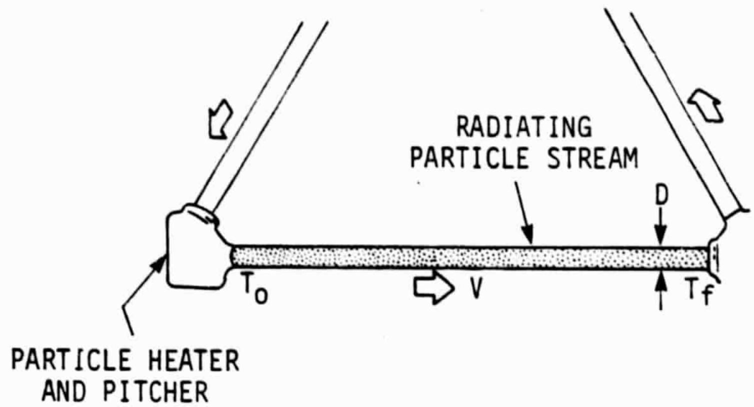
(b) Emitter Out Of Beam

Figure 2.67. TELEC Electrode Configurations (Reference 194).

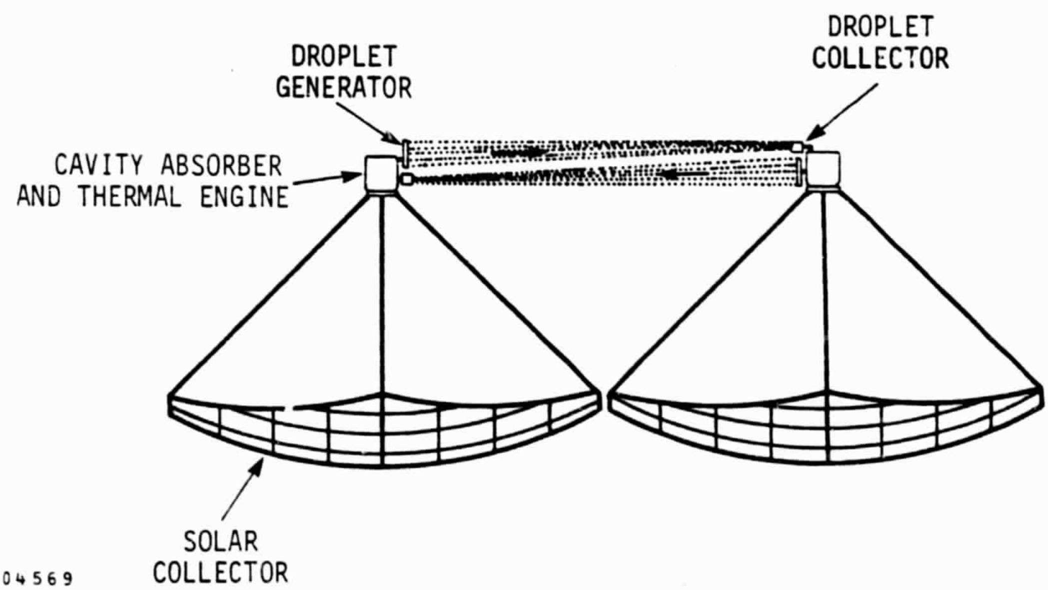
It should also be pointed out that the power-specific weight of these heat pipes follows approximately the inverse T^4 dependence associated with heat pipes at other temperatures and does not have any additional weight savings other than that associated with higher temperature operation. They also suffer from the same puncture liabilities as other conventional fluid cooled radiators.

There are several novel radiator concepts such as the dust,(215) droplet,(216) and belt radiators(217) that involve material transfer as part of the cooling and radiating process but which are not subject to puncture failure and which have much larger radiator areas without the conventional structural constraints. Both the dust and droplet radiator are based on the idea that a large radiator area can be achieved in this way and that meteorite strikes will simply remove a small portion of the "coolant" materials as they pass through the sheet of dust or droplets enroute from a transmitter nozzle to a "catcher" placed some distance away. The droplet concept appears to be more attractive because of the ease of moving liquids within the power system and because direct contact heat exchange by heat conduction and forced convection within the system is simplified relative to solids-solids heat transfer. However, liquids will tend to have a higher vapor pressure than solids, so that materials loss may be a problem. Even if only a small fraction of the liquid evaporates during a mission lifetime, the transport and condensation of the coolant onto other parts of the spacecraft exterior could be detrimental. Examples of these two concepts are shown in Figure 2.68.

Initial estimates of the droplet radiator power-specific weight suggest that an order of magnitude reduction might be possible.(216) This would be an extremely significant advance if it materializes, since it would affect the competitiveness of all thermal power systems relative to photovoltaics systems in terms of both reliability and weight. To this end there is a need for careful evaluation of the droplet radiator concept to accurately account for all of its components in a systems context in order to estimate its weight. Initial experiments on droplet formation and radiation are in progress.(216) If these prove successful, then some of the



(a) Dust Radiator



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(b) Droplet Radiator

Figure 2.68. Dust (a) and Droplet (b) Lightweight Waste Heat Radiator Concepts for Space Power Systems. (References 215 and 216, respectively)

critical technology should be tested; for example, a multi-droplet injection system and the droplet catcher.

The belt radiator suffers from much the same problems as the dust radiator except that solid-solid heat transfer is more easily accomplished. A study is in progress now to compare droplet radiators to belt radiators.(217) It will be useful to review the results of that study before attempting any further research on belt radiators.

2.4.8 Power Transmission Conclusions

Application of power beaming technologies to support space propulsion systems or space bases is clearly some years in the future. Therefore, the energetics technology activities appropriate in the next few years are those essential to understanding the feasibility of these concepts. There are three main feasibility issues:.

1. Phase Control: The need to reach high phase front precision over large antennae at frequencies of 100 GHz and more indicates the need for new phase control approaches. The phase control technologies employed in solar power satellite research used RF phase distribution and RF phase conjugation to achieve phase control. Phase distribution systems typically operated at something like 400 megahertz. Since phase errors are multiplied by the frequency multiplication ratio, the use of phase distribution at this frequency and multiplying up to 100 GHz or more for beam production would magnify 1 degree phase errors to something like 360 degrees. Therefore, frequencies and high d/λ ratios more nearly like optical techniques may be appropriate. This would involve free space illumination from the back side of the transmitting surface for phase distribution and interferometric techniques with feedback to provide the beam shaping

through active structures to manipulate the transmitter surface. A traveling wave interferometric technique may be applicable here.[218]

2. Millimeter and Optical Wavelength Receivers: The principal issue here is the development of a rectification device that can convert these high frequencies to DC electric power. Possible candidates include microrectenna, photovoltaic cells, and laser heat engines.

3. High Voltage Power Supplies: In the eventuality that gyrotron devices are used as millimeter wave generators, then high voltage power supplies will be required. High voltages are likely to be needed for other high power spacecraft applications; for example, to reduce on-board power distribution losses. Voltages of interest range from 1 kilovolt to 100 kilovolts. High voltage power processors will also be required.

In addition, the very basic question of the relative merits of power beaming versus on-board power production should be reviewed thoroughly as the technology of laser and rf sources develops. Specifically, the relative advantages of new laser sources should be analyzed. These include the suggestion of a reversible chemical laser for space power beaming. Direct and indirect optically pumped lasers need to be carried through the proof-of-concept experiments to determine their actual potential. These latter two laser concepts can obviate the need of high voltage power sources listed as the third feasibility issue above and, therefore, have a chance of leap-frogging over a formidable technical obstacle.

Significant advances appear to be in the offing through the use of high temperature materials in heat pipes. We recommend the following

topics for research in waste heat radiators, in addition to the Los Alamos heat pipe development program:

1. Droplet Heat Radiators: Test the critical technologies required for the feasibility of this concept and conduct a careful systems analysis and preliminary designs to determine its true power-specific weight.

2. Evaluate the desirability of Zero-G experiments to demonstrate the operation of condensating radiators and long heat pipe operation (e.g., see Reference 219).

2.5 Power Processing

2.5.1 Introduction

In the past, power processing on-board spacecraft has mainly performed the conversion of low voltage DC power from photocells or thermoelectric cells to a wide range of on-board power uses from high frequency communication output and very steady voltage and current supply conditions required for scientific instruments (e.g., computers, data storage, detectors) to battery charge and discharge voltages and currents. Redundancy is required in order to guarantee reliability for the mission lifetime. Also, the power processing units, usually inside the spacecraft, must be cooled in order to maintain proper operating temperatures. In short, the power processing category includes all of the power busses, power conversion (electric to electric) needed to connect supply to end-use, and the auxiliary equipment (coolers, radiators, control systems) needed to keep these components operating properly.

As power requirements rise into the 100 kW range and higher, the absolute size of the power busses and converters will make it more attractive to increase the voltage and frequency of the power delivery system by reducing line losses and making voltage conversions more efficient. Upper limits in voltage and frequency will be imposed by the voltage characteristics of the primary electric power sources (e.g.,

photocells or thermal power supplies) and by the length and configuration of the power busses (ie., "antennae" and transmission line effects).

The specific mass of power control or processing units is currently above 10 kg/kW_e.[220] By 1990, development of current technology should succeed in decreasing the specific mass of such units below this limit. The functions being supplied by the power processing units will also be increasing their requirements on the system, especially in the area of data handling (i.e., scientific and communications satellites). Therefore, the challenge to power processing technology is to handle higher voltages in space and higher powers (multi-hundred kilowatts) and to reduce weight (and cost) of the processing units.

2.5.2 Requirements

Present power processing systems are based on 28-60 Volt, 0~50 amps regulated current supplies. Such systems typically must be maintained below 250 $^{\circ}C$ to avoid degradation of insulators and conducting connection and to keep temperature dependent resistivity from rising too high. Also, solid state components lose their efficiency at higher temperature. The maximum temperature constrains the temperature at which waste heat can be rejected. A minimum temperature, typically of -20 $^{\circ}C$, is often imposed to prevent the extremes of thermal stress at electrical connections in order to maintain reliable operation over the mission life.

Higher power systems and larger areas over which power must be collected and distributed very quickly lead to much heavier power processing systems measured in mass per unit power unless higher voltages and higher temperatures can be utilized. Additional weight savings may be realized by faster switching devices to eliminate unnecessary inductor and capacitor weight.

For missions far from the earth, where message round-trip time exceeds the time needed for internal power processing response functions to varying internal and external power demands, fault correction, cycling,

etc., then a need exists also for autonomous control systems to monitor the processing unit and effect its operation to maintain its reliability.

Further, standardization of the power processor inputs and outputs with spacecraft user voltages, currents, and frequencies is extremely important in order to ensure a proper match between all of these components.

2.5.3 Power Processing Technologies

Power processing includes all the electronics and cabling to convert the output of the energy converter and/or the storage element into controlled, regulated power at the load. See Figure 2.69 for the blocks of a typical power processing unit.

This unit consists primarily of a few key generic component types, including active solid state switches, passive switches (diodes), capacitors, inductors, and conductors. Since future missions will involve operation of spacecraft at higher power levels, higher voltages and currents, and perhaps with lower weight requirements for power systems, there are needs in each component area for advanced technology elements. The following sections detail each component type as to status, needs, and possible targets of opportunity where leverage for significant advances appears to exist.

2.5.3.1 Switches

ACTIVE SWITCHES

The bipolar transistor is the workhorse of space power processing at present, with space-qualified components available at 28-60 volts, 0-50 amps, with switching speeds of up to 50 kHz.

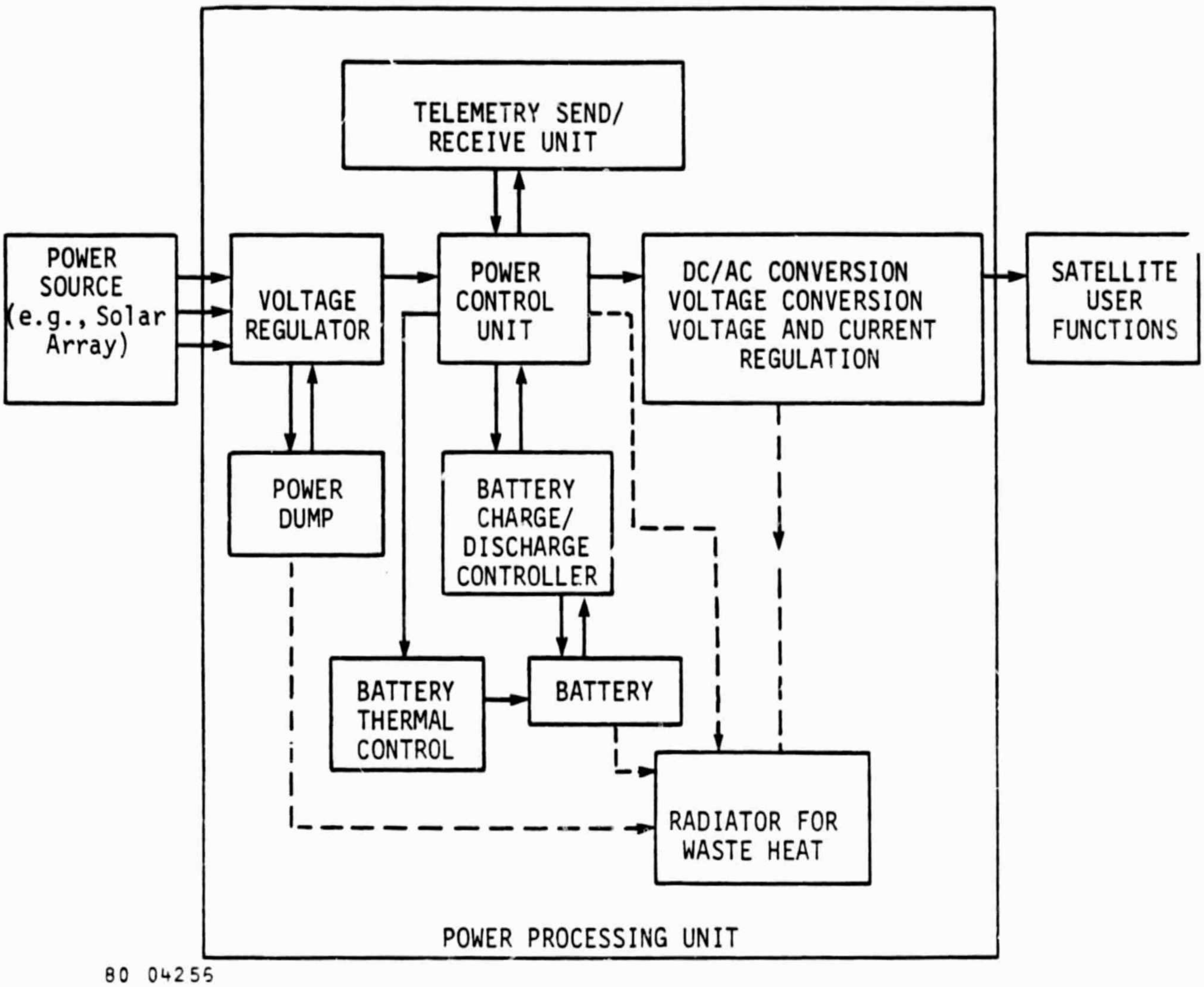


Figure 2.69. Schematic of Power Processing Unit.

DIODES

Present diode technology offers bipolar devices at hundreds of volts with switching speeds increasing with current capacity, from 30-100 nanoseconds at 5 amps to microseconds at hundreds of amps.

2.5.3.2 Capacitors

Capacitors consisting of foil wound packets play the classic role of capacitors in LC circuits to provide given tunable frequency output power. Tantalum capacitors offer high energy density, high current capability, and low dissipation factor up to 125 volts.

2.5.3.3 Inductors

Inductors also satisfy the usual role of shifting voltages up or down through inductive coupling and, as described above, provided the appropriate inductance in LC frequency synthetic (oscillator) circuits. Magnetic components at high frequencies must have low eddy current losses, low hysteresis losses, and high magnetic flux density capabilities. Presently ferrites and Moly-Permalloy Powder (MPP) cores are used for low power levels.

2.5.3.4 Conductors

Conductors, usually copper or aluminum wiring, connect most of the elements of power processing units to convey the power and control function from one point to the next.

2.5.4 Limit to Present Power Processing Technology

Presently available space quality transistors for high speed switching converters are available in the range of 28-60 volts, 0-50 amps, and 20-50 kHz. The associated tantalum capacitors, diodes, inductors, etc. are available also:

a. Transistor switches with Beta $\cong$ 10 up to 350 V

b. Diodes with switching times near 50 nanosecond, Schottky diodes with faster times for under 40 volts

c. Ferrite magnetic core material for switching applications

d. Tantalum capacitors up to 125 V - aluminum above that.

More than many other areas, power processing packages represent a synthesis of the available component technologies. Lack of any one component makes a design unmanageable.

Current programs include[221]

- Spacecraft Charging Program (high voltage systems interaction with the ambient space plasma) in cooperation with the Air Force.

- Automatic System Controls for on-board system monitoring fault identification, fault correction, and control (at JPL) using the Viking Orbiter solar array/battery power system.

- High Power System Technology Program (at MSFC) for multi-hundred kilowatt systems.

- Power Systems Modeling (at GSFC): AC/DC models for solar arrays, batteries, power processing, and control equipment.

- Power Component Development: high power switching transistors, inverters, converters, and circuit breakers.

In this latter program area, NASA expects to demonstrate:

1. Transistor power handling capability of 125 amps at 500 volts (and a gain of 10) with possible extension to a 1000 volt, 30 amp transistor.

2. SCR circuit breaker capable of handling 1 kV at 25 kW, allowing the use of 500 V (high voltage) power bussing system.

3. Bilateral power converters which transform AC polyphase powers to controllable AC or DC power weighing 1 kg/kW at 25 kW (used at base of solar array to convert solar array power to AC using a rotary transformer).

The technical challenges in power processing are to achieve high efficiency while maintaining low weight and cost. Higher efficiency means smaller solar arrays for a given power output as well as less waste heat to reject from the power processing units. Further, it is desirable to be able to operate the power processing units (that dissipate energy) at higher temperatures so that the waste heat radiator can be reduced in size. At present, component temperatures are limited by semi-conductor temperature constraints (i.e., for Silicon SRCs); using a different material that could operate at a higher temperature would be better.

2.5.5 Basis of Comparison

The level of performance to be used as a benchmark will be taken from an existing satellite power system operating with a photovoltaic cell power source and a nickel cadmium battery energy storage system. We have chosen the power system associated with the satellite INSAT-I as exemplifying the present state of technology.[222] In this system, power is bussed at DC voltages of 26.5 to 42.5 V, currents of 0 to 45 amps for average power levels of 940 watts, and a seven year design life. Power

switching is accomplished by Dc to dc converters which utilize magnetics and a hybrid microcircuit consisting of chip and wire components in a thick film substrate. The converter has an efficiency of 80% or better. Voltage control is accomplished with capacitors to limit the rate of change to less than ±3.5 V/ms. Battery discharge is controlled by parallel redundant discharge diodes. Any advanced or new technologies should provide a significant improvement over these performance levels in order to qualify for serious attention in the Advanced Energetics Program.

2.5.6 Application to Generic Missions

Future systems will press the limits by going to higher voltages and higher frequencies. All missions, including LEO and GEO, require power processing and benefit from advances via weight savings and/or higher efficiency.

2.5.7 Advanced Power Processing Technology

2.5.7.1 Switches

ACTIVE SWITCHES

Since the weight of the processor is dominated by inductor, capacitor, and heat sink, the use of faster devices results in 1/f reduction in filter weight while also reducing switching losses. Devices are available at voltages up to 400 volts in non-qualified form, but as the currents go up the speed comes down. A family of higher speed devices with multi-hundred volts and tens to hundreds of amps capability is needed.

The VMOS FET represents a quantum improvement in switching speed at high powers. Present development by the terrestrial power conditioning market has produced a rapidly improving series of devices by many suppliers, with voltages over 400 volts and currents into the tens of amps. It is vital that these devices be made available to the spacecraft designer for 100 kHz - 1 MHz switching of power. Lower "on" resistances are the key parameter at present. However, these devices may suffer from radiation effects as other MOS devices do. For example, early in 1980 a

VMOS power FET was tested for radiation resistance at MIT Lincoln Lab at 1.5 MeV. It failed at a total exposure of 30 Krads or 1 x 10^{12} electrons per square centimeter, a relatively low level. The mode of failure was a reduction in threshold voltage to below zero volts. This indicates a need for the evaluation of radiation effects and for either shielding or radiation-resistant device development for the generic class of VMOS power FETs.

Lightweight, solid state switches which are a close equivalent to relays are needed. Such developments would greatly improve reliability and life, for failed components and devices can more easily be switched out while retaining use of other components associated with the failed device. Multikilowatt spacecraft will have dozens of batteries, chargers, regulators, and other power components, and the problem of switching becomes formidable. Two important devices which are keys to this development are 1) the inverted transistor which has a voltage drop less than 0.1 V, but unfortunately has too low a breakdown voltage, less than 9.0 V; and 2) VMOS power FETs which have high breakdown voltage (35 to 90 v) and low leakage current when off (0.5 micro-amp) but too high a resistance when on (about 1.4 ohm at 1.0 amps). Research to improve these two devices is needed.

PASSIVE SWITCHES

Schottky diodes offer very high speed but at low voltages. To properly utilize a VMOS transistor at its highest speeds, faster high-voltage diodes are needed. These may be faster bipolar devices or higher voltage Schottky devices, the latter being most probable.

Both diodes and transistors require heavy heat sinks due to their low temperature limits. New semiconductor materials capable of higher temperature operation would reduce this weight.

2.5.7.2 Capacitors

High energy density, high current capability exists up to 125 V. Above this, there are low dissipation factor, low current devices or low energy density (aluminum) devices. There is a need for a new family of capacitors combining these features for multi-hundred volt systems.

2.5.7.3 Inductors

A new material capable of efficient high frequency operation at higher flux density, and usable for higher powers is needed. For example, metallic glass materials, such as Metglas by Allied Chemical Corporation, represent one possible approach to achieve these performance goals. Thin (1 to 3 mil) ribbons of amorphous material, made of metal-metalloid combinations, have been produced and made into transformers as large as 15 kVA. These units feature very low magnetization currents, low hysteresis losses, and potential for low eddy current losses.

The presently produced Metglas material, optimized for 60 Hz applications, is good for any use below 1 kHz and has core losses as much as 7 times lower than conventional transformers.

For higher frequency applications, a different material chemistry and the development of interlaminar insulation techniques will probably reduce the eddy current losses to allow very attractive designs.

2.5.7.4 Conductors

The large weight of copper distribution wiring may be reduced by using advanced high conductivity, low weight materials, such as those formed by "doping" materials in a carbon matrix with anisotropic properties. This represents the development of a long-term technology with significant potential. [illegible] present, even the problems associated with such components are not well defined.

2.5.8 Power Processing Conclusions

By focusing on the component level, the needs for space power processing have been treated at a basic technology level. The main thrust for new and advanced technology in this area comes from mission goals requiring higher powers and lighter weights. Power processing for multi-kW systems presents a whole new set of problems related to system size, heat loads, reliability, and distribution of power. Major advances appear to be possible in virtually every category of power system components reviewed. Specifically, we recommend the research be considered in the following areas:

1. VMOS FET's allowing higher frequency operation with much higher power gain compared to minority-carrier devices. Power supply frequencies from 100 kHz to 2 MHz can be achieved and, in general, weight is inversely proportioned to frequency. However, VMOS may be subject to radiation damage. This problem should be assessed and, if possible, hardened families of devices developed.

2. The above switching speeds are only possible if diodes can be developed which are fast enough. Below 40 V, Schottky devices do this. A family of higher voltage diodes with Schottky speeds and multi-hundred volt ratings are needed to match the VMOS capabilities.

3. Higher efficiency transformers are needed. As one possible example, new magnetic materials made of an amorphous metal ribbon are now being developed. This material has much lower hysteresis losses than steels, and may be able to replace ferrites and tapewound cores. At present, the material is excellent from 40 Hz up to 1 KHz. The material

resistivity must be increased and inter-layer insulation improved for use at higher frequencies to avoid eddy currents. This appears feasible but has not yet been pursued. Needed are:

- insulating layer techniques
- methods of applying to gapped components
- further material improvement to reduce eddy current losses

Potentially much smaller, lighter magnetic elements in 20 KHz to 1 MHz frequencies are needed.

4. Extension of tantalum or other high energy density capacitor technology to higher voltage levels.

5. Investigation of new conducting materials capable of maintaining high conductivity and lifetimes at lower weights than copper or aluminum.

In addition, we recommend that the following studies be carried out to develop additional data needed to evaluate the potential of advanced power processing technologies:

- Determine the critical problem areas in high power spacecraft processing and distribution systems emphasizing the consideration of high voltage level, high current level options and the interaction with the spacecraft environment.

- Determine the areas of application and need of energy storage for pulsed power amongst NASA's mission requirements.

- Conduct a systems study of autonomous controls of power system, especially the battery subsystem.

Section 3

MISSION ENABLING TECHNOLOGIES

3.1 Introduction

Advanced energetics technologies can enable new capabilities to be realized in missions already on the drawing board and may allow the conception of entirely new missions. The main questions are: What real mission needs exist for advanced energetics? How well can advanced energetics meet these needs? In which ways can these technologies enable new missions? The following discussion of generic missions points out specific needs and refers to advanced technologies which have the potential for satisfying these needs.

3.2 Low Earth Orbit Operations

Missions in low Earth orbits that will benefit from advanced energetics include manned and unmanned science, applications, and operations platforms as well as specialized single-purpose missions such as materials processing or space-based manufacturing. Mission planning for space platforms has concentrated on applications which are Earth-observing or Earth-oriented and on operational systems such as the proposed Space Operations Center. The latter is conceived as a manned platform to facilitate space operations including construction of large satellites, transportation servicing, and servicing of low Earth orbit missions or satellites.

The low Earth orbit environment presents certain problems to the energy supply designer. In order for the low Earth orbit to be readily accessible by the Shuttle, it must be placed at an altitude no higher than 500 kilometers and very likely will be placed as low as 400 kilometers so that the Shuttle can reach it without an orbit maneuvering system kit. The drag of power-intensive platforms in a low Earth orbit is dominated by the solar array. In order to compensate for drag, it is necessary to periodically resupply these vehicles with orbit makeup propellant. Such

resupply can be expensive in view of space transportation requirements. Consequently, there is a high payoff for improving the efficiency of the solar array to reduce its area and, therefore, its drag. Drag could also be reduced by using solar thermal (e.g., Brayton cycle) or nuclear power systems. Similar advantages will accrue to efficiency improvements in the power processing and energy storage systems.

Low Earth orbits experience roughly 15 shadow periods per day. During each shadow period available power must be supplied by batteries. The tendency in future systems is to consider longer and longer mission life periods. Over a ten year life, the battery storage system of a low Earth orbit spacecraft may experience over 50,000 charge/discharge cycles. Batteries for low Earth orbit spacecraft can be replaced by a Shuttle flight (or possibly by service from a co-orbiting Space Operations Center). There is a tradeoff between battery life, depth of discharge, and replacement cost. However, a significant value exists for improving battery life at a given depth of discharge. Similarly, the turnaround efficiency for the energy storage system provides the same benefit as increased efficiency of the solar array in reducing drag and orbit makeup propellant requirements.

Presently, for large-area long-life systems, the collision environment in low Earth orbit is dominated by man-made debris. The expected flux of objects ranging upward from a few millimeters in size is orders of magnitude greater for man-made debris than for the natural micrometeroid environment. The collision design requirements for objects of 100 square meters or more for extending periods in low Earth orbit is dominated by the problem of collisions with man-made objects from 1 to 10 centimeters in size. Crew compartments must be heavily shielded. However, for lightweight, large-area systems such as solar arrays, the only practical design approach is to ensure graceful degradation in the event of collision damage.

3.3 Scientific Missions

Scientific missions often place special constraints on spacecraft power systems in addition to those of performance, weight, cost, etc., which apply for all types of missions. The major areas of concern are (1) that some of these scientific missions must gather data in unusually hostile environments, and (2) that the power system must not interfere with the performance of the measurements.

Operation in Hostile Environments

Table 3.1 lists several possible future missions with unusual environmental requirements. In addition to those requirements, an important problem is due to the effects of cosmic dust on spacecraft. This problem is directly related to the collection and concentration of particulate debris and subsequent impact on solar cell obscuration, operation of high voltage power systems, and possible malfunction of other power components. This is an area deserving of further study.

Spacecraft Cleanliness

Nearly all magnetospheric, planetary, solar, and deep space scientific spacecraft carry instrumentation to measure the local charged particles and electric and magnetic fields and waves. Typical sensitivity or natural background levels are as follows:

a. DC magnetic fields: 1 Gauss at the sensor, which is often mounted on a boom to be far removed from spacecraft magnetism.

b. Electromagnetic and RF interference: See Table 3.2(a) and (b) for a typical instrument (Galileo).

c. Electrons: For energies above 30 eV, integral flu
[= number of particles $cm^{-2}s^{-1}$ with energy > E(MeV)] ≈

Table 3.1

Operation In Hostile Environments

Environment	Example	Duration	~Power level, kw
High temperatures	Solar probe (to 4 R_0)	1 day inside 10 R_0	1
	Encke rendezvous (0.3 AU)	~1 month	1
	Mercury orbiter	2 years	1
	Solar orbiter (4 R_0)	1-2 years	1
	Venus surface	1-2 years	1
Deep space (cold, long duration)	Outer planets	10-30 years	1
	Out of solar system (to ~100 AU)	30 years	1
High radiation	Earth orbit	1-5 years	several to hundreds
	Jupiter orbit	1-5 years	several
	Sun orbit	1-2 years	several
Dusty	Comet missions	~1 year	1 (plus that needed for solar electric propulsion, if used)

Table 3.2 (a)

Galileo Electric Field Sensitivity

Frequency Range	Integrated Electric Field
1 Hz - 4 kHz	0.5 μV/m in 30% bandwidth
4 kHz - 400 kHz	0.5 μV/m in 15% bandwidth
1 Hz - 2 kHz	50 μV/m
250 Hz - 85 kHz	50 μV/m
400 kHz - 10 MHz	0.5 μV/m in 1 kHz bandwidth between harmonics of 2.4 kHz power supply frequency

Table 3.2 (b)

Galileo Magnetic Field Sensitivity

Frequency Range	Integrated Magnetic Field
1 Hz - 1 kHz	40 μγ in 30% bandwidth
1 kHz - 100 kHz	30 μγ in 15% bandwidth
1 Hz - 2 kHz	2mγ
250 Hz - 85 kHz	1mγ

$1/E^2$. At lower energies, the total integrated fluxes are of the order of 10^8 $cm^{-2}s^{-1}$.

d. Cosmic ray protons: In the energy range 1 keV to 1 MeV, integral flux $\simeq 3/E^{2.6}$.

The outer spacecraft surface is normally required to be an equipotential, within a few Volts. We note that solar panels are often a greater source of RF interference than RTGs, but that the radioactive decay products of the RTGs tend to interfere with the cosmic ray measurements.

Power Requirements of Scientific Experiments

In general, the scientific experiments which are most demanding on the spacecraft power system are active magnetospheric experiments in which ions, electrons, or plasma waves are injected into the magnetosphere, and the response of the magnetosphere to this perturbation is measured at both the point of injection and elsewhere. At present (e.g., Spacelab 1), the power available for wave injection is ~8 kw in one 15 minute pulse each 4 hours. For future experiments, hundreds of kw at hundreds of Volts with a 50% duty cycle would be desirable. Future particle injection experiments will need many amps at tens to hundreds of kV; a few percent voltage control would be adequate for these experiments.

Accurate high voltage control is required for particle analysis instruments, especially those which use solid-state detectors. The present state-of-the-art is ~30 kV with ~0.1% stability. Instrument performance would be improved if the voltage level could be increased to ~100 kV.

3.4 Power Transmission

A great deal of power transmission analysis and some experimentation has been conducted, mostly with respect to the use of this technology to transmit power from space to Earth for eventual commercial use. However, there are space-to-space transmission applications that might prove attractive under certain circumstances. Examples include the use of space-

to-space transmission to provide power to lunar or Mars surface stations. A space-based power transmission system might prove preferable for such an application as compared to a nuclear reactor system. Due to the long duration of the lunar night, lunar-surface-based solar arrays with battery storage are impractical. Freed from the requirement to select a power transmission frequency that can easily transmit the Earth's atmosphere, one could deal with millimeter wave or laser systems at much higher frequency and transmit much smaller blocks of power over the distances from the L1 or L2 lunar libration points to the lunar surface. The transmission distance is somewhat less than that from the surface of the Earth to geosynchronous orbit. Laser power transmission systems with net power outputs as low as a few hundred kilowatts might very well be feasible. The accomplishment of such power transmission capability for long time lunar surface missions will require substantial advances in steady-state laser technology and laser light-to-electric conversion technology. At somewhat higher power levels, millimeter wave RF systems might well be used with technology more nearly like that presently in use for large phased array systems. These concepts have been discussed in greater detail in Section 2.

3.5 Solar Electric Propulsion

Solar electric propulsion offers an attractive capability for advanced solar system exploration missions as well as a potential economic advantage for large scale cargo delivery between low Earth orbit and geosynchronous or other high Earth orbits.

For solar system exploration missions there is a technology performance breakpoint above which the mission performance improves dramatically. The effect was discovered empirically during numerical integrations of solar system escape missions. In summary, if the power to mass ratio of the electric propulsion system is above a certain level, then the system can accelerate to a high velocity before it is too far from the sun to derive power from it; otherwise, the system will gain thrust too slowly and achieve only a modest velocity at a distance so far from the sun that it cannot gain much more energy and can only spiral slowly away from

the sun. The performance breakpoint occurs approximately at an acceleration level of 10^{-3} m/sec^2 at Earth's distance from the sun. With a typical electric specific impulse of approximately 5000 seconds, this requires a specific power of 30 watts of jet power per kilogram of vehicle mass. This specific power is about 5 times that of the solar electric propulsion system (SEPS) presently under study by NASA. The SEPS will use planetary flybys to achieve a slingshot effect to reach the outer planets. With a sufficiently high performance solar array, this might not be necessary and could reduce the mission time to just a few years. Reaching 30 watts per kilogram would require improvements in solar arrays as well as improvements in lightweight power processors.

The operation of a solar electric propulsion system between low Earth orbit and geosynchronous orbit entails a very high level of radiation exposure in the Van Allen radiation belts. With today's photovoltaics, this presents a serious problem of radiation degradation. There are several possible avenues of technology development that could minimize this difficulty. Clearly, improved performance reduces trip time and reduces to some degree the degradation due to radiation. More important would be a means of restoring lost array output through annealing of the solar cells, selection of a very radiation-hard photovoltaic material, or selection of a design approach in which the cells may be adequately shielded from radiation.

Some of the thin film technologies may offer promise of increased radiation hardness, but too little experimental data exists today to make a firm conclusion in this area. Subjects promising for research include thermal annealing of silicon and galium arsenide solar cells, radiation hardness of thin film galium arsenide and other thin film systems, and design studies of thermal photovoltaic systems to assess efficiency and performance potential.

3.6 Advanced Space Propulsion

The importance of advanced space energetics to advanced space propulsion can hardly be overstated. In this discussion we consider advanced space propulsion to be propulsion systems capable of making space flight to the moon and planets routine. Some of the difficulties associated with interstellar flights are also illustrated.

Advanced energetics may also be important to Earth launch propulsion, but this is forseen as further in the future. Up to 2 orders of magnitude cost improvement beyond the projected costs for the space shuttle is potentially achievable through improvements of reusable liquid propellant rocket launch vehicles. Since this is an evolutionary rather than a revolutionary path, it is quite likely that advanced energetics will not be applied to launch propulsion until such time as these evolutionary improvements have been exploited. It is likely that the next 30 years or so will be devoted to driving the cost of transportation to low Earth orbit down to the $10 per kilogram range, somewhere near the lower limit achievable with chemical rocket technology.

Advanced energetics has potential application, in a timeframe parallel with this 30 years, to propulsion from Earth orbit to more distant destinations. Chemical rocket systems are very marginal for space transportation beyond low Earth orbit because of their relatively poor specific impulse or jet velocity. Advanced energetics offers the possibility of much higher specific impulses with acceptable thrust to weight ratios.

A relatively simple analysis can shed considerable light on the performance levels desirable for routine transportation within the solar system. This simple analysis recognizes that systems capable of desirable trip times will have enough thrust such that to first-order approximation the sun's gravity field can be ignored and a simple, straight path acceleration and deceleration algorithm can be used to establish trip times of interest. Figure 3.1 was derived for acceleration to distant objects using this simple algorithm. The chart is drawn for one way acceleration.

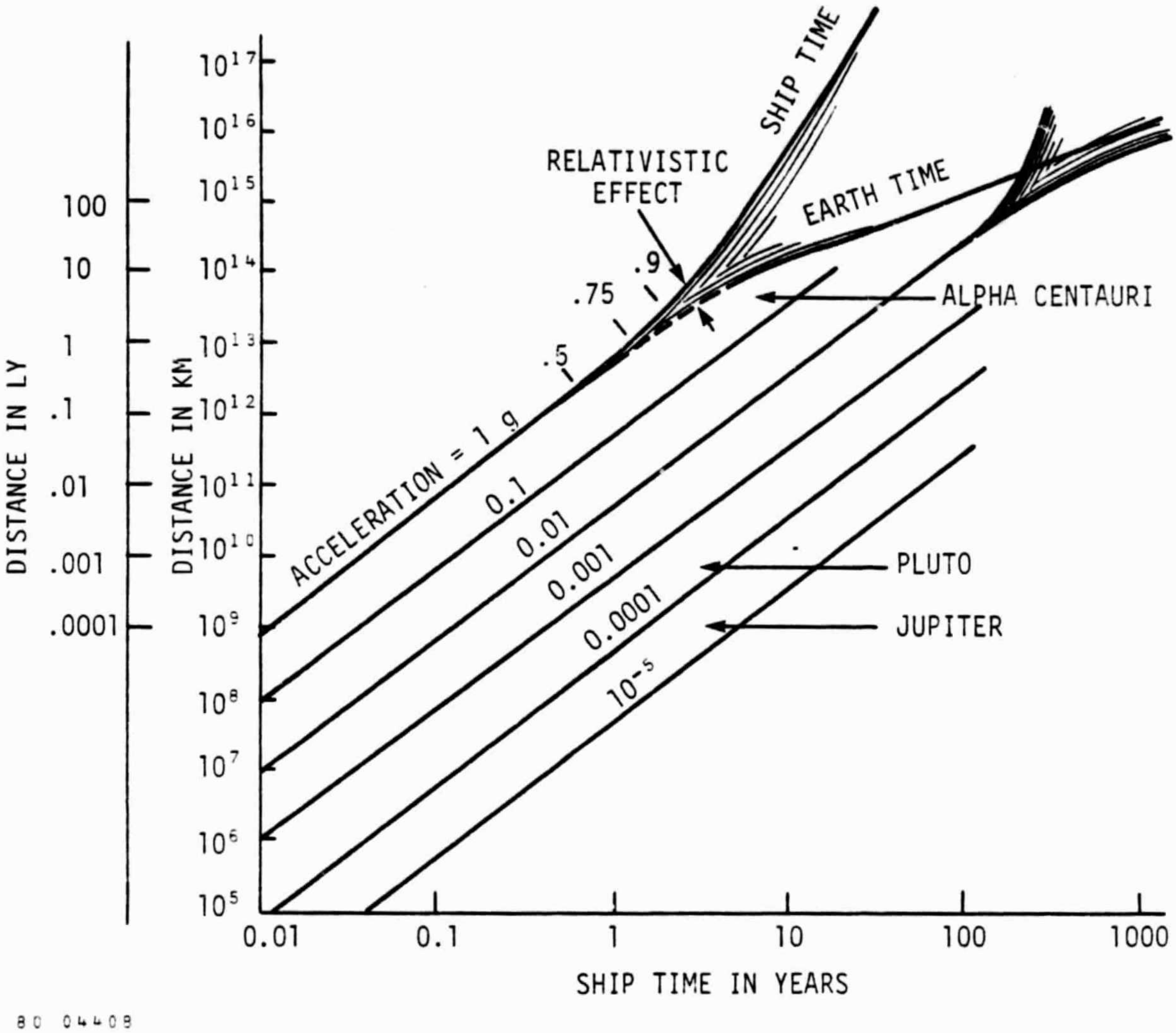


Figure 3.1. Trip Time Relationships.

C-4

If deceleration at the target is desired, then one can cover twice the distance indicated in twice the time indicated.

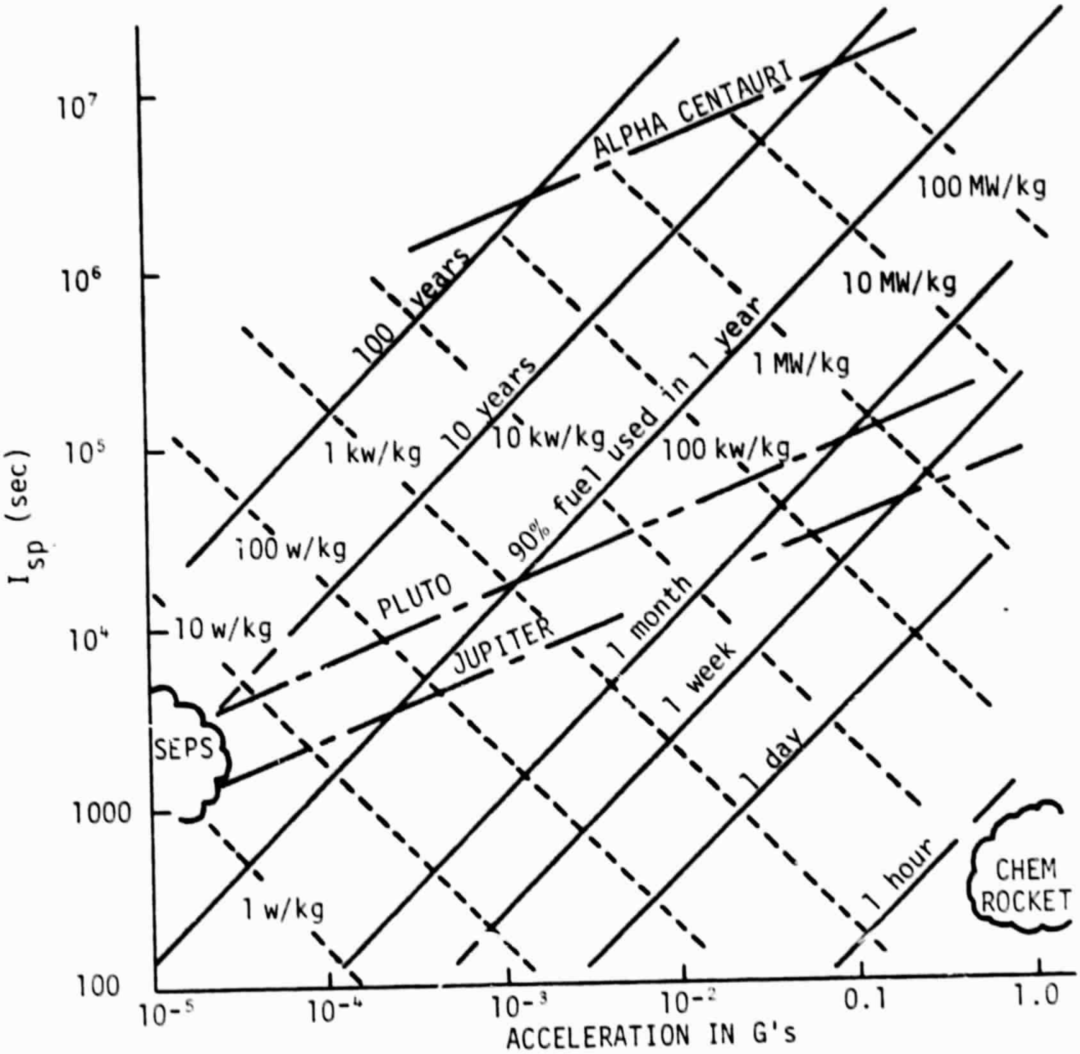
Numerical integration was used to establish the relativistic effect at very high velocities. The relativistic effect is not very important for conceivable systems of practical interest. Even if we presume a perfect matter annihilation engine in which matter is converted to collimated energy directed as thrust, the vehicle will have converted 90% of its mass to energy by the time it reaches the point on the 1 G curve labeled .9.

Relativistic effects were determined using the special relativity algorithms. Since the analysis was based on an inertial frame of reference, it is unnecessary to consider general relativity even though the vehicle is accelerated.

Representative distances within the solar system and to one of the nearest stars are shown. The solar system distances to planets nearer than Jupiter are not enough less than Jupiter to merit additional lines on the curve.

The two principal figures of merit for an advanced propulsion system are its specific impulse, or jet velocity, and the representative acceleration it can develop. Figure 3.2 illustrates the performance potential of space propulsion systems as a function of these two parameters. Several parameters are cross-plotted on the curve. First, since propellant consumption is proportional to acceleration and inversely proportional to specific impulse, diagonal lines trending upward to the right are lines of constant time required to consume 90% of the ship's mass as propellant. These lines are positioned such that the acceleration during the propellant consumption time is constant; in other words, thrust is decreasing as propellant is consumed. The curves would shift slightly for constant thrust, but not very much.

The chart is constructed on the premise that a power limited system will always be used in a continuous thrusting mode. One can show that if the propulsion system is power limited, then to reach any given destination in the shortest possible time one should operate the propulsion system all



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Plot is inaccurate below 10^{-4} g's; tends to underestimate trip time.

Figure 3.2. Space Propulsion Performance Regimes.

the time and select the highest specific impulse that one can utilize to reach the objective in the indicated time.

The curves for Jupiter, Pluto, and Alpha Centauri are cross-plotted on this curve based on where they cross the acceleration and time lines on the prior curve. One can see that accelerations on the order of 10^{-2} G's with specific impulses in the 10 to 20 thousand second range would allow travel anywhere within the solar system in a matter of months, and that to begin to think of travel to the stars one would need to improve these capabilities, each by something like 4 orders of magnitude.

Where are we today? Two areas are labeled on the curve - one for chemical rockets and another for SEPS. Chemical rockets are actually energy limited systems; that is, their ISP is limited by the energy of propellants and are not really applicable to this curve. However, it is of interest that their acceleration capabilities generally exceed 1 G and their specific impulses are typically 2 to 500 seconds. Solar electric propulsion systems now in development will provide an effective vehicle acceleration on the order of 10^{-5} G's. The bare propulsion system can do better, but once the mass of propellant and payload are taken into account, this is about the figure. Forseeable advances in solar array power processing and thruster technology might improve this by up to a factor of 2 to 6 to achieve 10 watts per kilogram for the entire propulsion system. A 10 watt per kilogram propulsion system can reach Jupiter in just over a year.

Large advances are needed to get into the range of real interest. 100 watts per kilogram to 1 kilowatt per kilogram of vehicle mass would begin to open up the solar system to routine travel. These, again, are vehicle levels, and the bare power system level should be roughly a factor of 10 better or 1 to 10 kilowatts per kilogram. By way of comparison, modern aircraft jet engines deliver approximately 10 kilowatts of thrust power per kilogram of engine weight. Liquid rocket engines do something like a factor of 100 better, roughly 1 megawatt per kilogram of bare engine weight. These systems, however, can dump the cycle waste heat overboard in the jet. In the area of space propulsion, it is likely that only direct

nuclear systems of some sort will achieve these kinds of performance potentials. Systems which must generate electricity, reject waste heat through space radiators, and use the electricity to accelerate a propellant will have a very difficult time ever reaching such performance levels. Nuclear fission systems are specific impulse limited to something like 2000 seconds ISP, even for very advanced concepts. Fusion systems may eventually achieve such performance levels if charged particle reaction micro-explosion systems can be developed.

3.7 Conclusions

Consideration of new mission capabilities has emphasized the need for high efficiency solar cell arrays, solar thermal (dynamic) power systems, or nuclear power systems to reduce satellite drag in low Earth orbit (LEO). More efficient power systems will also help to reduce array size and conserve station-keeping propellant. Long lifetime mission requirements in LEO have exacerbated this problem. Longer lifetime batteries are needed for the same reason; improved battery charge-discharge efficiency will also help reduce solar collector sizes. Scientific missions place particularly severe requirements on the power system because they must often operate in hostile environments (e.g., near the sun, in energetic charged particle streams, or in cold, long duration missions) and simultaneously maintain the operation of delicate instruments which are sensitive to the electric and magnetic fields induced by the power system itself. Power system shielding or concepts which do not generate electromagnetic fields are essential. In special cases (i.e., ionospheric particle and wave injection experiments), high voltage, pulsed power systems will be needed in the hundred kilowatt and hundred kilovolt range with a 50% duty cycle. Power transmission would help to eliminate the need for batteries in those missions where the stored power requirements are extensive enough to make remote power supply costs allowable; it might be feasible to meet power demands from 100 kW up to tens of megawatts in this way.

Advanced propulsion, including solar electric propulsion, clearly benefits from the development of new and advanced space power systems. Easy travel within the solar system and the possibility that star travel might be eventually achievable provides a long range motivation for investigating very high specific power sources, such as gaseous nuclear rockets, and fusion sources, such as an updated thermonuclear version of the Orien concept using repetitive micro-explosions to provide high specific impulse thrust.

In the following section both routine and advanced generic missions take an important part in the evaluation of new and advanced energetics technologies. The foregoing discussion provides the background and motivating information for carrying out this part of the evaluation. In an effort to ensure that the use of mission analysis is continued as a tool for determining needs in advanced energetics, we recommend that studies be carried out periodically to investigate new mission applications and the enhancement of existing mission capabilities through the use of advanced energetics technclogies.

Section 4

COMPARATIVE EVALUATION

4.1 Introduction

As a result of the technology assessments in Sections 2.1 to 2.5 and the mission analysis of Section 3, we have identified numerous prospects having potentially high payoff for advanced space energetics. In this section these technologies are rated according to their probable payoff, the technical risks involved in achieving high performance, and the level of investment required to demonstrate their potential. Only the top 43 prospects were considered. The potential for enhancing planned missions and for the enablement of new missions is also used to help evaluate these technologies.

The committee's judgement played the most important role in selecting and rating the technologies. Clearly, different results will be obtained when a different group of people evaluate the same technologies, depending on their judgement and the weighting factors employed. Nevertheless, it is possible to draw useful information from this process, which has reinforced the committee's judgement concerning the highest priority technologies. These lead to the recommendations contained in Section 5.

4.2 Approach

The relative merits of the technology items were compared in terms of "intrinsic" and "applications" factors. The intrinsic factors were:

> Investment - What investment is required to realize significant progress on this item?
>
> Risk - What is the risk of failure to achieve significant progress?

<u>Payoff</u> - How great is the payoff (i.e., performance improvement) if the venture is successful?

Each factor was rated low, medium, or high based on the judgement of the committee. Judgement used in assigning the ranks of low, medium, and high implicitly accounts for the degree to which individual technologies might exceed the performance benchmarks for energy storage, conversion, transmission, and processing, the existence of technological barriers to their development, and the estimated cost of that development.

An applications rating was developed by selecting thirteen representative new missions from NASA planning literature. The missions are comprised of three generic "routine" missions and some additional imaginative missions. The "routine" missions are widely discussed in future space mission literature. The advanced missions were derived from NASA material on imaginative mission sources such as the space systems technology model.

A wide variety of potential applications fall under the category of high power spacecraft. In this discussion a high power spacecraft is one that uses electrical or other power at several kilowatts or above. It excludes power beaming spacecraft, such as solar power satellites, which are covered under imaginative missions. There are a great number of potential space applications, science, communications, or manned missions requiring high power spacecraft with power levels ranging from a few kilowatts to at least a few megawatts and perhaps more.

Outer planet exploration was divided into a routine category and an advanced category. The advanced category includes such missions as Mars sample return and manned planetary missions.

Space industrialization in the routine category includes primarily such missions as space processing of materials in zero gravity. High power, advanced communications satellites can fall into either category.

The source material for imaginative missions included more than 50 specific missions. Many of these require advancements in engineering or scientific technique in areas other than energetics. Insofar as energetics are concerned, most of these missions fall into the high power spacecraft category or require high power spacecraft for support, e.g., a manned space construction base to build some of the very large instruments. Others fall under such categories as advanced planetary exploration, planetary surface or atmospheric vehicles, hostile environment vehicles, or may require advanced space propulsion to enable their accomplishment. Several of the missions have unique needs for space energetics and were explicitly called out in the matrix. One mission - asteroid deflection - found little in the advanced energetics research areas that was applicable. Asteroid deflection will require some form of very advanced space propulsion and, in that regard, the energetics areas applicable to advanced space propulsion would also be applicable here.

The matrix is coded in three ways. First, a blank means the energetics technology either has no application or is judged very unlikely to have an application. The second category, P, indicates a possible or potential application. It is assumed that the advanced energetics technology will be successful, but if a P is entered it means that even if successful it might not be used. Finally, an X is used to indicate definite or important applications where, if the technology is successfully developed, it will almost certainly be used.

4.3 Results

Since the bulk of the study was devoted to understanding the status and intrinsic performance potential of advanced energetics concepts, the most significant ratings employed in this evaluation are those associated with payoff, risk, and investment. The mission application ratings were necessarily more superficial due to the scope of the study. Nevertheless, the mission ratings do indicate preliminary perceptions of the utility of various advanced concepts. The results of these ratings are shown in Table

4.1. Section numbers refer to those sections of this report where a particular technology is discussed. These results are taken into account but form only part of the process of arriving at the final recommendations for research summarized in the next section.

Table 4.1

Advanced Energetics Technology Ratings

	Sect. Ref.	Intrinsic			"Routine" Missions				"Advanced" Missions								
		In-vest ment	Risk	Pay-Off	High Power Spacecraft	Outer Planet Exploration	Space Industrial	Solar Power from Space	Space Nuclear Waste Disposal	Advanced Planetary Exploration	Permanent Lunar Outpost	Planetary Surface or "Air" Vehicles	Asteroid Deflection	Hostile Environment Vehicles	Extraterrestial Engineering	Space Settlements	Advanced Space Propulsion
1. Nickel Electrode Structure and Electrolyte Interaction	2.3	L/M	M	M/H	X	P	X	P		X	P	X		P	P	P	P
2. Silver Hydrogen Battery Study	2.3	M	M	M/H	X	P	X	P		X	P	X		P	P	P	P
3. High Temperature Battery Study	2.3	H	H	H	X	P	X	P		X	P	X		X	P	P	P
4. Microprocessor Back-up Power Supply	2.3	L	L	L	X	X	X		P	X	X	X		P			
5. Flywheels for Energy Storage	2.3	M	M	H	X	P	X	P	P	X	P	X		P	P	P	P
6. Flywheel Energy Storage/Attitude Control Combination	2.3	L	L	M	X		X	P							P	P	P
7. TE/TI Compound Converter	2.2	M	H	H	P	X			X	X	P	P		P			P
8. Low Work Function Particulate TE Converter	2.2	M	H	H		X			X	X	P	P		P			P
9. High Temperature Electrolysis with Low Temperature Fuel Cell	2.2	M	M	H	P		P	P		P	P	P			P	P	
10. Rotating Bed Recuperator	2.2	M	M	H			P	P	P	P	P				P	P	P
11. Non-Equilibrium MHD	2.2	M	M	M			P	P	P		P			P	P	P	P
12. Graphite Particle Thermal Storage	2.2	L	L	M			P	P			P	P		P	P	P	
13. Free Piston Expander	2.2	H	M	H			P	P	P	P	P	P		P	P	P	P
14. High Temperature Solar Receiver	2.1	M	M	H			P	P							P	P	P
15. Energy Exchanger	2.2	H	M	H			P	P							P	P	P
16. Droplet Radiator	2.4	M	H	H	P	P	P	P	P						P	P	P
17. Rotating Bed Nuclear Power Reactor	2.1	H	M	H		P	P	P	P	P	P			P	P	P	P

H = High, M = Medium, L = Low, P = Possibly applicable, X = Definitely applicable, blank = not applicable

Table 4.1

Advanced Energetics Technology Ratings
(continued)

	Sect. Ref.	Intrinsic: Investment	Intrinsic: Risk	Intrinsic: Pay-Off	High Power Spacecraft	Outer Planet Exploration	Space Industrial	Solar Power from Space	Space Nuclear Waste Disposal	Advanced Planetary Exploration	Permanent Lunar Outpost	Planetary Surface or "Air" Vehicles	Asteroid Deflection	Hostile Environment Vehicles	Extraterrestial Engineering	Space Settlements	Advanced Space Propulsion
18. Large Photovoltaic Array Deployment	2.1	H	M	H	X		X	X					P		X	X	X
19. Lightweight Solar Concentrators	2.1	H	M	H	P		P	P							P	P	P
20. Electrochemical Heat Engines	2.2	M	H	L	P		P	P		P		P		P	P	P	
21. Intercalated Graphite and Doped Plastic Conductors	2.5	M	H	M	X	P	X	X		P	P				P	P	P
22. Alkali Metal Thermoelectric Converter	2.2	M	H	M			P	P				P		P	P	P	P
23. Efficient Low Temperature Refrigerators	2.2	M	H	M	X		X	P		P		P		X	X	X	P
24. Superconducting Energy Storage for Pulsed Power	2.3	M	M	M			X	P	P		P		P	P	P	P	P
25. Micro-rectenna Converters	2.4	L	H	M			P	P			X	P			P	P	P
26. High Efficiency Transformers	2.5	L	L/M	M	X	P	X	P		X	P	X		P	P	P	
27. High Temperature Solid State Power Processing Components	2.5	H	H	H	X	P	P	X	P	P	P	P		X	P	P	P
28. Millimeter Phased Array Transmitters	2.4	L/M	M/H	M	P		P	P		P	P	P			P	P	P
29. Radiation Resistant/Annealable Photovoltaic Cells	2.2	L	L	M	X		X	X	P	P					X	X	X
30. Advanced Photovoltaic Cell Encapsulation	2.2	L	M	M	X		X	X	P	P					X	X	X
31. Multi-Band Gap Photovoltaic Cells	2.2	M	M	H	X	P	X	X	P	P					X	X	X
32. High Concentration Ratio Photovoltaic Cells	2.2	L	L/M	M	P		P	P	P	P					P	P	P
33. Photovoltaic Cell Efficiency Improvement	2.2	M	L	M	X		X	X	P	P					X	X	X
34. Long Heat Pipes	2.4	L	M	M	X	P	X	X	P	P	P	P		P	X	P	P
35. Efficient Laser Transmitter	2.4	M	M/H	H	P		P	P			P				P	P	P
36. High Temperature Insulator for TI Converter	2.2	M	H	H	P	P	P	P	P	P	P	P		P	P	P	P

H = High, M = Medium, L = Low, P = Possibly applicable, X = Definitely applicable, blank = not applicable

Table 4.1

Advanced Energetics Technology Ratings
(continued)

		Intrinsic			"Routine" Missions				"Advanced" Missions								
	Sect. Ref.	In-vest ment	Risk	Pay-Off	High Power Spacecraft	Outer Planet Exploration	Space Industrial	Solar Power from Space	Space Nuclear Waste Disposal	Advanced Planetary Exploration	Permanent Lunar Outpost	Planetary Surface or "Air" Vehicles	Asteroid Deflection	Hostile Environment Vehicles	Extraterrestrial Engineering	Space Settlements	Advanced Space Propulsion
37. New, High Temperature Thermoelectric Materials	2.2	M	M	H	P	P	P	P	P	P	P	P		P	P	P	P
38. Thermophotovoltaic Converter	2.2	M	H	M/H	P		P	P							P	P	P
39. High Temperature Turbine	2.2	H	M	M			P	P	P	P	P			P	P	P	P
40. Thermally Regenerative Fuel Cell	2.3	L	M	M	P	P	P	P	P	P	P	P		P	P	P	P
41. Advanced Nickel Hydrogen Battery Technology	2.3	M	L	L/M	X	P	X	P		X	P	X		P	P	P	P
42. Superionic Solid State Conductors	2.5	M	H	H	P		P	P	P	P	P	P		P	P	P	
43. High Power Solid State Relays	2.5	M	H	H	X	P	X	X	P	P	X	P	P	P	X	X	X

H = High, M = Medium, L = Low, P = Possibly applicable, X = Definitely applicable, blank = not applicable

Section 5

RESEARCH RECOMMENDATIONS

The evaluation of advanced energetics technology begun in Section 4 is carried to its final stage in this section. Priorities for ranking the advanced energetics technologies evolved during the course of this study and are summarized below. In ranking these technologies the committee relied strictly on their own judgement. A more objective ranking procedure should be applied at some point in the future to verify the results presented in this section. The outcome of the committee's evaluation forms the basis for a series of research studies and project recommendations presented here for the NASA Advanced Energetics Program.

5.1 R & D Priorities

R & D priorities for the Advanced Energetics Program have been selected which emphasize the role that this program can play in supporting high risk but high payoff ideas which are key technologies in the sequential development of more complete, high performance space power systems. This rationale evolved over the course of the study from numerous observations of technologies which were or were not being cultivated for space power systems as well as the fortunate conclusion that there are many potentially high payoff concepts to be explored.

As a consequence, those technologies rated as having high payoff were ranked highest, with the ratings of risk and investment cost playing a less important role. This approach constitutes a narrowed focus to the ratings presented in Section 4. Since the mission applications were not the direct subject of this study, the mission ratings were used only to better qualify the nature and direction that research should take on the proposed topics, instead of using mission ratings to explicitly rank the technologies.

The list of technology R & D project areas evaluated in Section 4 has also been evaluated with respect to the sequence required for orderly

exploration of related concepts, most notably in the thermal conversion and power beaming areas where the feasibility of a primary technology should be established before the rest of the elements are investigated. This evaluation also involved an identification of the long lead time technologies such as high power, high temperature components and materials requiring immediate attention. We have also endeavored to recognize those project areas which may receive concurrent support by parallel programs within NASA or other agencies, with the understanding that such support might serve similar goals.

5.2 Project Area Recommendations

As a result of the evaluation process described above, we recommend that the following project areas be considered for the NASA Advanced Energetics Program:

PROJECT AREAS

Highest Priority (high payoff, low to moderate risk and cost):

Flywheels for Spacecraft Energy Storage
* Rotating Bed Recuperators for High Temperature Power Cycles
High Temperature Solar Receiver
Multi-Bandgap Advanced Photovoltaics
New, High Temperature Materials for Thermoelectrics
Nickel Electrode Structure and Electrolyte Interaction

Second Priority (high payoff):

High Temperature Batteries
Thermoelectric/thermionic Compound Converter
Thermoelectric "packed-bed" Converters
High Temperature Electrolysis with Intermediate Temperature Fuel Cell
Free Piston Expander
* Energy Exchanger Expander
* Droplet Radiators

* Rotating Bed Reactor (RBR) System
* Large Area Photovoltaic Array Deployment Schemes
  Lightweight Solar Concentrators
* Millimeter Phased Array Transmitters and Receivers
  High Temperature Solid State Components
  Super Ionic Solid Conductors
* Efficient Laser Transmitters
  High Temperature Insulators for Thermionics

<u>Third Priority (moderate to high payoff and low cost):</u>

  Flywheel Energy Storage/Altitude Control Combination
* Graphite Particulate Thermal Storage
* Microrectennas for Monochromatic Sources
  High Efficiency Transformers
  Advanced Photovoltaics:
    Radiation Resistance (including annealing)
    Encapsulation
    High Solar Concentration Cells (high intensity, high temperature)
    Efficiency Improvement of Single Cells
* Long Heat Pipes (flexible joints, high specific power)
  Thermally Regenerated Fuel Cell

Because the thrust to higher power is a natural, underlying theme for the Advanced Energetics Program, we have identified with an asterisk those project areas which relate specificially to high power systems.

These recommendations include technologies such as the advanced energy storage concepts which could be brought into a state of development where flight testing could take place, on a relatively short time scale in some cases, which would benefit a large number of planned Earth orbital missions involving various degrees of solar occultation, high power delivery, long life, and high reliability. The advanced thermal conversion concepts recommended above span technologies which could radically improve the efficiency and power levels of space power systems over current RTGs

and photovoltaic cell systems using solar energy and/or (in the case of the high temperature expander element) nuclear energy. The power beaming concepts would enable new mission capabilities such as dispensing with energy storage requirements on LEO and GEO, orbital transfer, and other planetary surface and orbital missions. Lastly, the advanced power processing concepts impact virtually every mission conceivable, especially in the high power end of the mission spectrum where processing efficiency and waste heat disposal are important problem areas.

The application of program priorities in the energy conversion area is straightforward: the leading criteria are to support technologies leading to higher power, reliable, lightweight systems. In the field of photovoltaics, higher powers can be achieved by increasing the collection area: a project concept of investigating novel deployable large arrays has been identified. The project area involving multi-band gap photovoltaic cells has a high potential for increasing the overall efficiency of such conversion. We have also identified a class of advanced photovoltaics which involve radiation resistant/annealable cells, advanced encapsulation techniques, high concentration ratio photovoltaic cells, and improved efficiency of single cells as an important project area.

In the field of thermal energy conversion, scaling to higher powers and lighter weights will require larger, lighter weight radiators. Two approaches have been identified: long heat pipe radiator concepts and novel droplet radiator concepts. High temperature radiators of necessity require even higher temperature thermal converters. Several high temperature conversion concepts have been identified, including the free piston expander/generator and the energy exchanger-turbine concepts. These, in turn, require high temperature sources such as the Rotating Bed Reactor System or lightweight, high concentration ratio solar concentrators. In large sizes (i.e., at high powers), such collectors must be carefully configured as well as lightweight. High temperature solar receivers will also be required for this option; for example, the particulate (e.g., RBR), doped-gas, or alkali-metal solar receivers. A critical component category for high temperature Brayton cycles is

exemplified by the rotating bed recuperator project area. Similarly, high temperature nuclear reactor concepts (e.g., RBR) are also desirable, but experiments may be beyond the scope of the Advanced Energetics Program because of the expenditures required.

Direct energy conversion thermal power system projects leading to higher specific powers include the advanced thermoelectric and thermionic project areas listed above and the novel concept of high temperature electrolysis coupled with an intermediate temperature fuel cell. A companion program in novel high temperature insulators for thermionics and other high temperature, advanced energy conversion techniques is also recommended.

Energy storage is needed mostly for missions involving solar occultation (e.g., LEO, GEO, Moon Surface, Planetary Orbiter, etc.) and for high power communications during short intervals. In this sense, improvements in energy storage have a very wide impact. The specific form of energy storage will depend on the conversion system. In particular, thermal energy storage and thermochemical energy storage are two areas selected for study. These areas are represented by graphite particulate thermal storage concepts and thermally regenerative fuel cells. Flywheel energy storage systems, the nickel electrode structure for advanced batteries, and high temperature batteries also show high potential for scaling to higher powers and for improved storage potential for converters which produce electricity without thermal or chemical energy as intermediate steps. The superionic solid conductor project area would contribute generally to high temperature battery, fuel cell, and electrolysis systems.

The greatest advances in power transmission are likely to come in the use of lasers and phased millimeter arrays. NASA's needs are for continuous (e.g., days to weeks) high power output and intermittent power for 35 to 70 minutes in the case of LEO and GEO solar occultation. It may be in NASA's interests to orbit power stations to accomplish its goals, in which case solar powered lasers and microwave transmitters may be attractive in terms of weight and scalability. The Advanced Energetics

Program needs to determine the best power transmission alternative from a systems point of view, including the problems of transmission and conversion at the receiving end as well as the features of the central power satellite itself. High efficiency receiver concepts, including microrectenna and millimeter wave receiver concepts, have been selected for further study.

Lastly, power processing would benefit enormously from lower losses and lighter radiator masses. Again, this can be accomplished by operating the radiator and, hence, the power processing equipment at higher temperature. High temperature solid state power processing components have been selected as a primary project area. Similarly, novel materials such as Met Glas are recommended for investigation related to transformer and other inductive components.

Those technologies which enable the use of other advanced power system components include, for example, the lightweight large solar collector, novel and high temperature radiators, high temperature recuperators, and high temperature solar receivers as technologies which must precede the development of high power, solar thermal, or nuclear power systems. Similarly, high efficiency laser receivers will enable laser power transmission to be used. Novel large deployable arrays and more efficient photocells will also allow higher power solar photovoltaic arrays to be used. These technologies deserve emphasis early in the Advanced Energetics Program because without them many of the other technologies selected for investigation would not work well.

Those technologies affecting the largest number of missions, mainly the energy storage and power processing concepts, also should be emphasized because their payoff is felt numerically even with modest advancements in their performance.

We also recommend that the following study topics be considered for the NASA Advanced Energetics Program. The purpose of these topics is to improve the state of understanding and data enough to evaluate the potential for improved performance in particular areas of technology and to

help establish firmer research priorities through a comparison of competing technologies. Without any preference intended by their order, these recommended topics are:

STUDY AREAS

1. Evaluate NASA's needs for high power nuclear sources and compare to alternative solar power systems.

2. Evaluate the relative advantages of concentrator photovoltaics versus flat photovoltaic arrays.

3. Evaluate the relative advantages of solar thermal versus photovoltaic power systems.

4. Evaluate the relative advantages of photovoltaic array deployment versus array assembly in space for higher power systems.

5. Determine the merits of power beaming versus local "on-board" power generation.

6. Review and evaluate alternate high temperature battery candidates.

7. Review and evaluate alternate high temperature gas expanders for thermal power systems.

8. Determine the critical problem areas in high power spacecraft processing and distribution systems, emphasizing the consideration of high voltage level, high current level options and the interaction with the spacecraft environment.

9. Evaluate the desirability of Zero G studies (e.g., to demonstrate the operation of condensating radiators, long heat pipes, etc.).

10. Investigate new mission applications and the enhancement of existing mission capabilities through the use of advanced energetics.

11. Compare the relative merits of thermophotovoltaic, thermionic, and thermoelectric power systems.

12. Evaluate the relative advantages of new laser sources for space power transmission.

13. Determine the need for energy storage for pulsed power amongst NASA's mission requirements.

14. Conduct a systems study of autonomous controls of power systems, especially the battery subsystem.

5.3 Conclusions

The outcome of this study has yielded several notable results; namely, that large advances in performance are potentially feasible in the areas of energy storage and power processing technologies through the exploration of advanced concepts. Advanced solar and nuclear energy technologies have the potential for lightweight, high power and high thermal conversion efficiencies. New mission capabilities may also be enabled, principally in the area of thermal energy conversion and power transmission.

Clearly, a large list of interesting and useful advanced energetics R & D topics has emerged during this study. This list should be reviewed and revised periodically as the technologies develop and as NASA's priorities change. The important features of the technologies recommended

are that they have the potential for large improvements in performance in a significant number of generic mission categories and/or they show very strong promise of enabling entirely new missions, as discussed in Section 4. Hence, the payoff in supporting R & D in these areas would be felt widely throughout NASA and would raise the agency's ability to respond to new missions and to new space requirements.

Appendix A

INDIVIDUALS CONTRIBUTING TO THE STUDY

L.W. Slifer	NASA-Goddard Space Flight Center
R.M. Jones	Jet Propulsion Laboratory
G.O. Fitzpatrick	Rasor Associates
G. Walberg	NASA-Langley Research Center
A. Pozwolski	Rue de la Plaine, Paris
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N. Elsner	General Atomic
J. Palmer	Hughes Research
R. Beverly	Consultant
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W. Jones	Lockheed Missiles and Space Company
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A. Hertzberg	University of Washington
M. Wrighton	Massachusetts Institute of Technology
J. Rather	BDM Corporation
K. Billman	Electric Power Research Institute
J. Wheatley	University of California at Los Angeles
M. Coombs	Garrett AiResearch
R. DeYoung	NASA-Langley Research Center
N. Jelufka	NASA-Langley Research Center

I. Meyers	NASA-Lewis Research Center
R.E. English	NASA-Lewis Research Center
R.C. Finke	NASA-Lewis Research Center
H. Brandhorst	NASA-Lewis Research Center
K.S. Jefferies	NASA-Lewis Research Center
L.H. Thaller	NASA-Lewis Research Center
J.F. Morris	NASA-Lewis Research Center
B. Wilson	Sandia National Laboratories
B. Beverly	Boeing Engineering and Construction
C.J. Swet	Consultant (formerly Department of Energy, Division of Energy Storage)
R.D. Smith	Rocket Research Company
R. Duscha	NASA-Lewis Research Center
J. Marten	Oak Ridge National Laboratories
A. Chalfant	United Technology
H. Pearlman	Atomics International
R. Rose	Westinghouse
J. Kerrebrock	Massachusetts Institute of Technology
D. Rosa	Montana State University
H. Isaacs	Massachusetts Institute of Technology
J. McBreen	Massachusetts Institute of Technology
C. Oberley	Wright Patterson Air Force Base
B. Bartholow	Department of Transportation
L. Belove	Marathon

R. Brodd	Exide
E. Cairns	Lawrence Livermore National Labs
A. Charkey	ERC
E. Cupp	Eagle Picher
J. Dunlop	COMSAT
H. Frank	Jet Propulsion Laboratory
H. Killian	Aerospace Corporation
L. Nuttal	General Electric Company
H. Seiger	Consultant
E. Seo	Gates
R. Spriggs	National Academy of Science
O. Wagner	U.S. Army Research, Ft. Monmouth
B. Walsh	Argonne Labs
J. Werth	Exide
D. Davis	Rockwell International
S. Hamilton	Bendix
B. Stemple	Allied Chemical
N. Bennett	Sperry Flight Systems Division
D. Rabenhorst	Johns Hopkins Applied Physics Lab
P.A. Studer	NASA-Goddard Space Flight Center

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